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Reconstruction of the continental glaciation in the northern slope of the Jizera Mts.

Rekonstrukce zalednění na severním svahu Jizerských hor

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Abstract: Methods of trimline identification were applied in the northern slope of the Jizera Mts. The weathering limit separating ice-scoured terrain from frost-weathered areas was investigated with Schmidt Hammer rebound testing, rock outcrops morphology mapping, blockfields mapping and weathering pits measurements. These methods were applied in six profile lines across the slope, including the relief from the foothills up to the summits. The first three methods showed good evidence of weathering limit, while the latter proved unusable for trimline determination. All the profile lines brought very similar altitudes. The resulting altitude of trimline was delimited at 470–490 m a.s.l. With respect to the limitations and accuracy of the methods, the trimline must be regarded rather as a zone ranging circa ± 20 m from this altitude.

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Introduction

The Pleistocene continental ice sheet reached the northern Bohemia region several times. According to present knowledge the ice sheet covered the Frýdlant upland and reached the foot of the northern slope of the Jizera Mts. two times.

Both the vertical and horizontal maximum extent of the glacier in the northern Bohemia were studied and discussed a lot in the past. The summary of former knowledge about the extent and age of continental glaciation was published by Sekyra (1961), Šibrava and Václ (1962) and Šibrava (1967). The maximum vertical extent of the glacier in the northern slope of the Jizera Mts. was estimated by Chaloupský (1989) at about 560 to 600 m a.s.l. Králík (1989) enlarged the number of document points during the revision research and distinguished four glacier advances, two of them during Elster and two in Saale glaciation. Králík (1989) was also the first who proved that the ice exceeded the Oldřichov Col (478 m a.s.l.), reached the area south of it and deposited the glaciofluvial sediments there. Oldřichov Col is still the highest location of proved glacial extent in the whole Frýdlant spur and it is a key point for the glacier extent delimitation.

The vertical glacial extent in most of the northern slope of the Jizera Mts. is deduced from the elevation of the Oldřichov col. The second key point for vertical glacier delimitation is the top of the glaciofluvial accumulation (450 m a.s.l.) situated above the town of Hejnice. According to these key points Králík (1989) delimitated the glacial trimline in the northern slope of the Jizera Mts. approximately between 450 and 500 m a.s.l. Although the exact extent of the glacier was never proved, this line is still considered as valid.

Nývlt (1998, 2003, Nývlt – Hoare 2000) studied glacial sediments in the region of northern Bohemia. Results from the Jeřice valley sediments enabled to accurate the idea of the ice exceeding the Oldřichov Col.

Former studies in the Jizera Mts. were focused mainly on glacial sediments. By contrast, this research is aimed at erosion surfaces that are most common in the northern slope of the Jizera Mts.

For determining of maximum vertical extent of ice sheet during the last glaciation the periglacial trimline method is used (Ives 1978, Nesje et al. 1994, Ballantyne 1994, Ballantyne et al. 1998). Trimline is defined as the border between periglacially modelled and glacially eroded relief. The part of the slope under the trimline was glacially exarated and the soil cover removed. On the other hand, the area above the trimline was exposed to long-term periglacial conditions and intense frost weathering during the glacials. Thick blockfields and high tors characterize the relief of these areas.

As the North Bohemia region was glaciated in Elsterian and Saalian (Králík 1989), all the landforms are much older than those of the last glaciation in North Europe or North America, where the trimline method is usually applied. The contrast between periglacially and glacially modelled relief was overprinted by younger geomorphologic processes during the long-time period following the glacier retreat. Nevertheless, the rate and type of weathering supposedly still differ in both parts of relief.

Authors use several methods to determine the weathering limit and to differentiate the characteristics of relief and rock outcrops above and under the trimline. These are Schmidt Hammer rebound values applied on the outcrops (McCarroll et Ballantyne 2000, Ballantyne et al. 1998, Ballantyne 1994), the differences in rock outcrops morphology (Phillips et al. 2006, André 2004), weathering pits measurements (Hall – Phillips 2006, Hubbard – Glasser 2005), mapping of blockfields and periglacial weathering covers (Ballantyne et al. 1998, Ives 1978).

In the northern slope of the Jizera Mts. only the Schmidt Hammer rebound value was applied from these methods so far in a pilot study by Traczyk and Engel (2006), who determined the upper ice sheet limit to 425 m a.s.l, and by Janásková and Koubová (2007). The latter was a study of about 100 sites measured by Schmidt Hammer and the trimline was delimited between tors and the other types of outcrops at altitude of 430–500 m a.s.l.

The aim of this research is to determine the ice sheet limit in the northern slope of the Jizera Mts. using the abovementioned methods, which proved good abroad.

Study area

This research was conducted in the steep northern slope of the Jizera Mts. These mountains belong to the Sudetes Mts. and are situated in the northern Bohemia. The study area is characterized by multivarious relief, including both the foothill with glacially modelled smooth relief and steep slope up to summit peaks, which reach up to 700–900 m a.s.l. The northern slope is dissected by erosion valleys and several small ridges rise few kilometers northwards (Fig. 1).

Except for the smooth foothill relief, a lot of shattered rock outcrops occur on the slope and on the small ridges. The rock outcrops extremely differ in their shape. In the foothills there are low elevations regarded as roches moutonnées (Janásková 2009). By contrast, the outcrops show no traces of glacial erosion in the higher parts of the slope. Particularly on the summits many huge tors are typical.

The study area bedrock is composed of granite in two types: porfyric coarse-grained biotitic granite and porfyric medium-grained granite. The bedrock homogeneity is convenient for data collection and comparison, as the impact of rock type is minimized.

Methods

Site selection

All the measurements and mapping in the northern slope of the Jizera Mts. were conducted in profile lines across the slope. Each of them includes the relief from

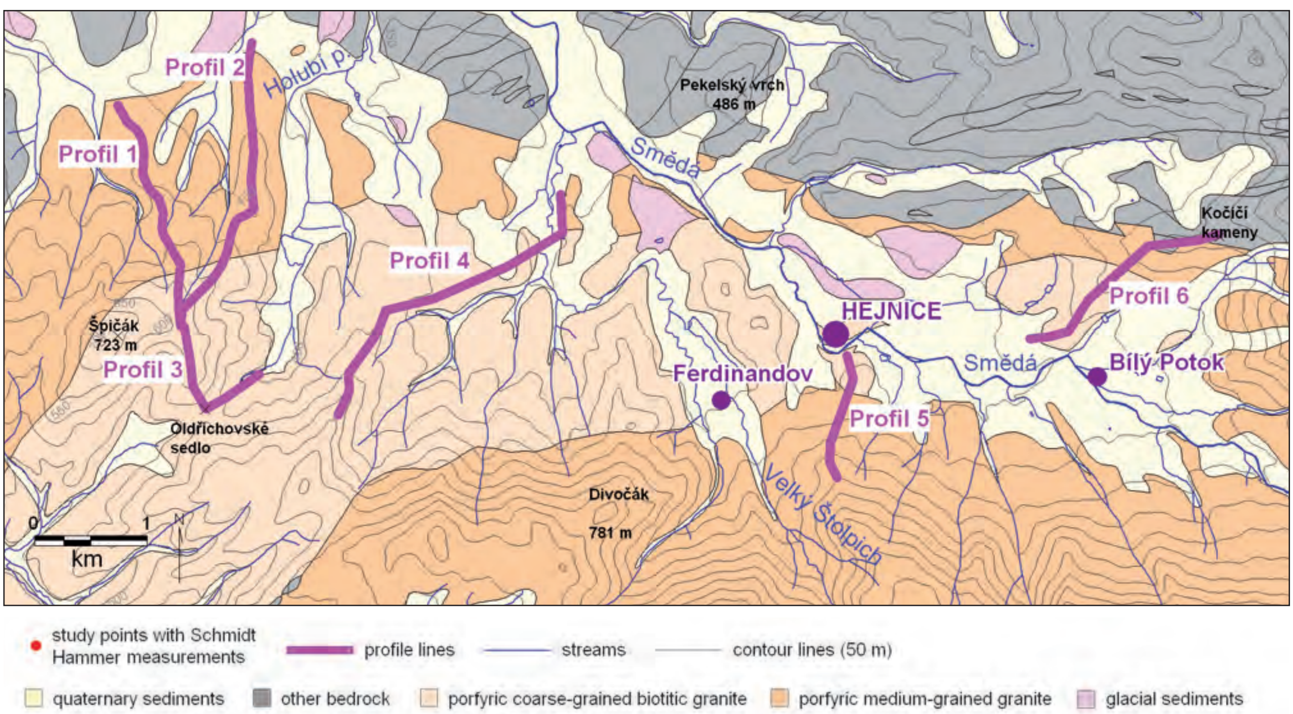


Fig. 1. Study area, geological setting and profile lines with study points.

the foothills up to the summits. The profile lines take place on the top of small ridges in order to avoid erosion valleys, provide similar character of erosion and accumulation processes on the profiles and thus enable their comparability. Total of six profiles were located, their positions are showed on the map (Fig. 1).

Three of the methods (the differences in rock outcrop morphology, weathering pits measurements, mapping of blockfields and periglacial weathering covers) were used throughout the whole profile length. The method of Schmidt Hammer measurements was applied on study points evenly distributed on each profile. Total of 38 points were used, at least 5 points per each profile.

Schmidt Hammer rebound measurement

The Schmidt Hammer rebound testing is used to measure the hardness of rock surfaces and to determine relative rate of rock weathering (Malhotra 1976, Sjoberg 1990, Katz et al. 2000, Sumner – Nel 2002). This method was already used for determining weathering contrasts under and above trimline e.g. by Ballantyne (1997), Ballantyne et al. (1998), Anderson et al. (1998).

The surface hardness was measured using N-type of Schmidt Hammer in accordance with the technique cited by Matthews and Shakesby (1984) and Moon (1984). Total of 25 impacts of Schmidt Hammer were taken on each study site. The resulting rebound value (R-value) was calculated in three steps. Firstly, the arithmetic mean was calculated, then five most deviating values were removed and finally the arithmetic mean was calculated from the remaining 20 values.

Only horizontal surfaces were tested and the Schmidt Hammer was held perpendicular to the surface. The measurements were applied only on dry surfaces to prevent the influence of moisture content (Sumner – Nel 2002).

Total of 38 outcrops situated on profiles were measured. Two types of Schmidt Hammer rebound measurements were used on each site. Firstly, measurements were conducted on the naturally weathered rock surface of the outcrops. Secondly, the surface was polished by an electric grinder to eliminate any surface roughness. This technique is strongly recommended by Katz et al. (2000) or Malhotra (1976), as the standard deviation decreases and the measuring accuracy increases after polishing. The results of both types of measurements were analyzed separately.

The rock outcrop morphology mapping

To locate the trimline authors determine a weathering limit directly in field, by mapping the landscape contrast between glacially moulded and periglacially weathered parts of landscape (Ballantyne et al. 1998). In the Jizera Mts. the landscape contrast is overprinted by younger geomorphologic processes and is not obvious any more. Although, there are plenty of rock outcrops scattered throughout the northern slope, which vary in their morphology. The difference in the outcrop size, height and shape can be caused by various impacts, one of which is glacial erosion. Thus, instead of direct landscape contrast determining, morphology and size of single outcrops was mapped.

All the rock outcrops were mapped and measured on the topmost part of the ridges, where the profile lines are situated. The rock outcrops were divided in following types according to morphology and size:

- Tors – isolated rock, at all sides protruding above surrounding terrain. High tors (height more than 5 m), middle-sized (3–5 m high) and low tors (less than 3 m high) were distinguished.
- Cliffs – vertical or overhanging rock walls on the slope. High (more than 5 m), middle-sized (3–5 m high) and low cliffs (less than 3 m high) were distinguished.
- Boulder piles – the outcrops that felt to pieces and are composed of in-situ boulders.
- Low outcrops – isolated rock outcrops, which are much larger in plane than in height and are lower than 2 m.
- Roches moutonnées – smooth-shaped elevations, usually elongated and with asymmetric slopes.

Blockfields mapping

Autochthonous blockfields and periglacial weathering covers are geomorphologic evidence of former long-term periglacial conditions. The location and low limit of blockfields were used to determine glacial trimline e.g. by Ives (1978), Ballantyne et al. (1998) or Nesje et al. (2006).

Usually authors distinguish autochthonous blockfields formed from the underlying bedrock material and allochthonous blockfields that can be composed also from till-derived material. In the study area of the Jizera Mts., the material of blockfields is solely local granite. Despite it, blocks and blockfields could have been affected by mass movement processes such as solifluction or debris flow and transported downslope after deglaciation (Ballantyne et al. 1998). The genesis of the blockfield was usually not possible to distinguish and therefore only the lower limit of blockfield was mapped on every study profile.

Weathering pits

Weathering pits are common forms in granite landscape and they originate from selective weathering. The depth and size of weathering pits develop during the time: the longer a rock surface has been exposed, the larger and deeper the weathering pits are (Hubbard – Glasser 2005). Although it is still unclear how long it takes for these forms to develop, weathering pits can be regarded as a relative age-dating technique (Hubbard – Glasser 2005). Authors applied weathering pits measurements also in formerly glaciated terrain (Dahl 1966, Hall – Phillips 2006)

All the weathering pits situated on study profiles were mapped and their length, width and depth was measured. Based on their shape, the weathering pits were classified into five development stages according to Votýpka (1964):

1. initial stage – development of first small-sized hollows,
2. deepening – the walls of the pit are vertical or overhanging,
3. drainage channel development,
4. drainage channel deepening to the bottom, connection of several pits,
5. senile stage – further connection of pits leads to their destruction.

Results

Schmidt Hammer rebound measurements

The comparison of measurements on natural and polished surface

According to collected Schmidt Hammer data, a substantial increase in R-value range after surface polishing is evident (Fig. 2). On the natural surface the rebound value of single impact ranges between 15 and 51, while the range after surface polishing was from 18 to 66.

The difference between data measured on polished and natural surface decreases, as the altitude increases. Strongly weathered outcrops give smaller rebound values even if polished (R-value up to 35), but weakly weathered outcrops give usually much higher values after polishing (R-value even above 50). This increase of data range is important for emphasizing of contrast between more and less weathered surface.

While after polishing the range of collected data increases, the standard deviation for 25 impacts at a study site decreases. The average standard deviation on natural surface is 2.57, whereas after polishing 1.8 only. Accordingly, surface polishing before measurement causes better data accuracy.

On the Fig. 2 the type of granite is distinguished. The litologic difference between coarse-grained biotitic granite and porfyric medium-grained granite obviously does not significantly influence the R-value and therefore it is not differentiated in the further text.

R-values median contrast

The most important indicator of trimline is a sharp contrast in outcrops weathering under and above it. To determine the altitude with the greatest contrast, the median for the Schmidt Hammer rebound data above and under various altitudes was calculated. The resulting medians and their differences are represented in the Tab. 1. The most different median of rebound values was obtained for the altitude of 470 m a.s.l. (polished surfaces) and 450 m a.s.l. (natural surfaces).

R-values range contrast

A significant contrast can be observed also in data range above and under specific altitudes. The rebound value range under and above various altitudes was calculated and the results are represented in the Tab. 1. The abrupt change in the obtained rebound values range was obtained for the altitude of 490–500 m for polished surface and both 450–460 and 490–500 m a.s.l. for natural surface.

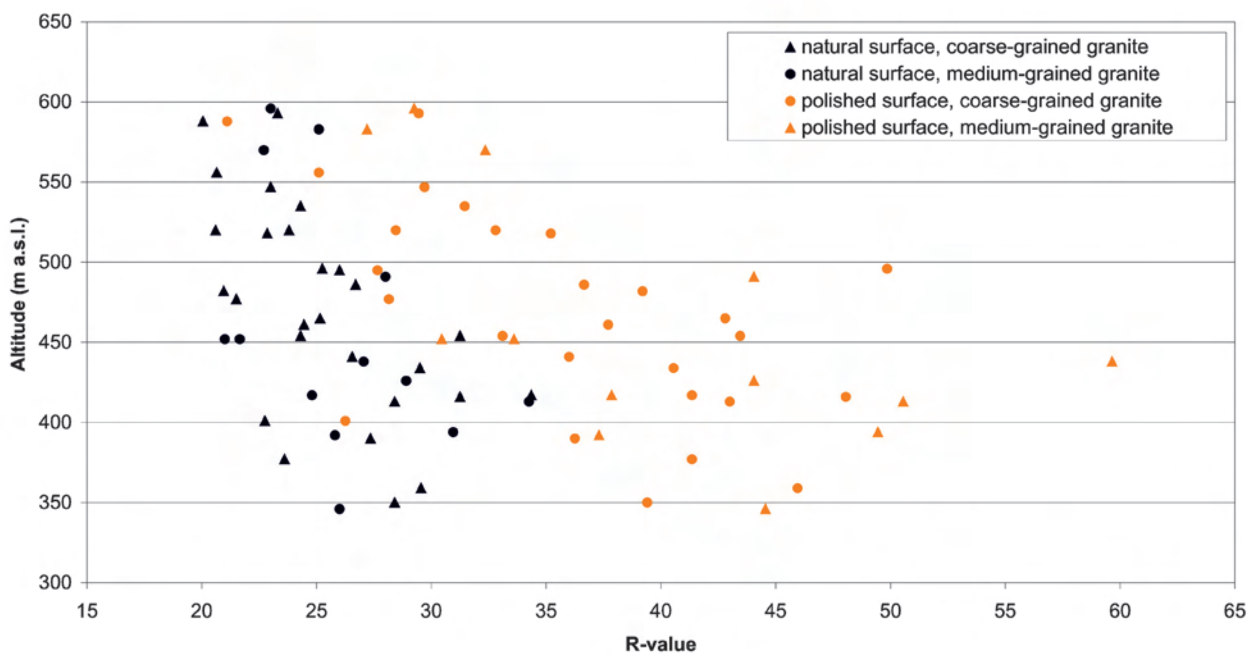


Fig. 2. Schmidt Hammer R-values.

Table 1. R-values median and range contrasts calculated for various possible altitudes of trimline

Altitude of possible trimline (m a.s.l.)	Schmidt Hammer R-values – polished surface						Altitude of possible trimline (m a.s.l.)	Schmidt Hammer R-values – natural surface					
	median			range (max-min)				median			range (max-min)		
	under trimline	above trimline	difference	under trimline	above trimline	difference		under trimline	above trimline	difference	under trimline	above trimline	difference
420	41.4	33.1	8.3	24.3	38.6	-14.3	420	28.4	24.3	4.1	11.6	11.2	0.4
430	42.2	33.0	9.2	24.3	38.6	-14.3	430	28.4	24.1	4.4	11.6	11.2	0.4
440	42.2	32.6	9.6	33.4	28.8	4.7	440	28.4	23.6	4.9	11.6	11.2	0.4
450	41.4	32.4	9.0	33.4	28.8	4.7	**450**	28.4	23.3	**5.1**	11.6	11.2	**0.4**
460	41.4	31.5	9.9	33.4	28.8	4.7	**460**	27.4	23.3	4.1	13.4	8.0	**5.4**
470	41.4	29.7	**11.7**	33.4	28.8	4.7	470	27.1	23.0	4.1	13.4	8.0	5.4
480	41.0	30.6	10.4	33.4	28.8	4.7	480	26.8	23.2	3.7	13.4	8.0	5.4
490	40.0	29.6	10.4	33.4	28.8	**4.7**	490	26.6	23.2	3.5	13.4	8.0	**5.5**
500	40.6	29.5	11.1	33.4	14.1	**19.3**	**500**	26.6	23.0	3.6	13.4	5.1	**8.4**
510	40.6	29.5	11.1	33.4	14.1	19.3	510	26.6	23.0	3.6	13.4	5.1	8.4
520	40.0	29.4	10.6	33.4	11.7	21.7	520	26.3	23.0	3.3	13.4	5.1	8.4
530	39.3	29.4	10.0	33.4	11.3	22.2	530	26.0	23.0	3.0	13.8	5.1	8.7
540	39.2	29.3	10.0	33.4	11.3	22.2	540	26.0	23.0	3.0	13.8	5.1	8.7
550	38.5	28.2	10.3	33.4	11.3	22.2	550	25.9	22.9	3.1	13.8	5.1	8.7
560	37.9	29.3	8.6	34.6	11.3	23.3	560	25.8	23.0	2.8	13.8	5.1	8.7

The contrast in data distribution is visible also in the Fig. 2. While under the altitude of 500 m the polished rebound values range from 26 to 60, above this altitude no higher value than 36 was obtained. All the outcrops above 500 m proved to be strongly weathered, whereas under this altitude both weathered and weakly weathered outcrops occur. On the natural surface, there are two altitudes where data range changes. Under 500 m a.s.l. (and 450 m a.s.l. on natural surfaces) the range of R-values is much wider than above these levels. This difference in data distribution above and under the altitude of 450–500 m can be caused by glacial erosion of outcrops below this limit. The glacial erosion could have caused the heterogeneity in rock outcrop hardness.

The contrasts in both median and range are significant and show marked change in data distribution. Thus the obtained altitudes definitely reflect the weathering limit. However, this limit remains generalized for the whole study area and is not specified for the profile lines.

The comparison of Schmidt Hammer R-values with the outcrops morphology

The results of the rock outcrop morphology mapping were used furthermore to evaluate the Schmidt Hammer data. The graph (Fig. 3a, b) represents the combination of the Schmidt Hammer rebound values and the morphology of outcrops.

There are in total six types of outcrops distinguished in the graphs. The low outcrops, boulder piles, low tors and the middle-sized tors are similar both in their rebound values and in their altitude. The resulting data of these outcrop types noticeably mingle with each other in the Fig. 3a, b. The roches moutonnées represent a group that differs a lot from the others in the graph of natural surface (Fig. 3a), but is similar to others and mingles with them in the graph of polished surface (Fig. 3b). In both cases the roches moutonnées have very high rebound values. The high tors are the only group that differs from the other outcrop types in lower rebound values and higher altitude and do not mingle with others much. The approximate altitude of the boundary between prevailing high tors and the rest of outcrops is about 500 m a.s.l. (Fig. 3a, b).

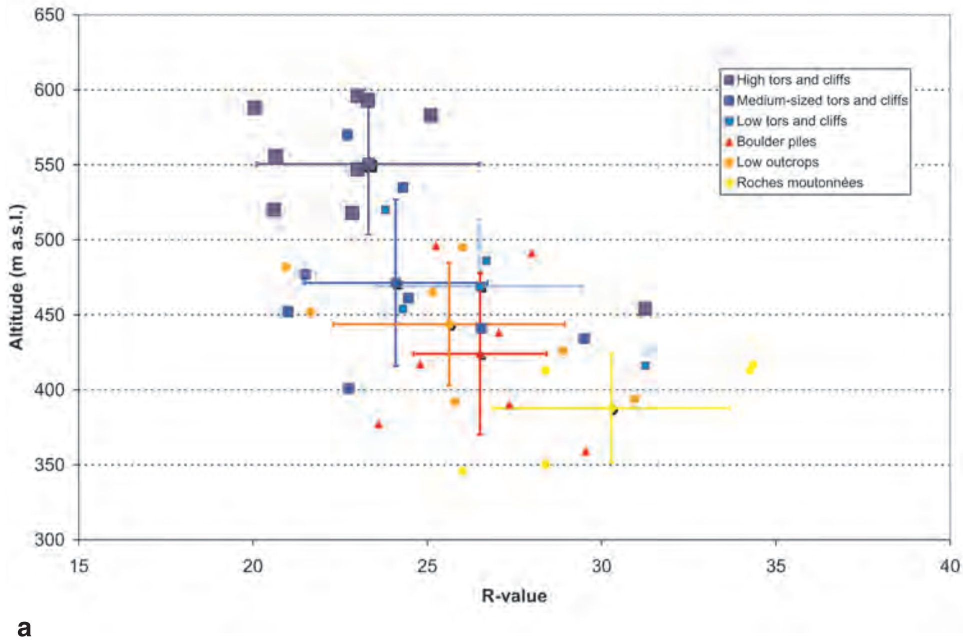
The symbol with black shade represents the average for the type of outcrop (both average of altitude and R-value). The error bars represent the standard deviations from average (in both directions of altitude and R-value).

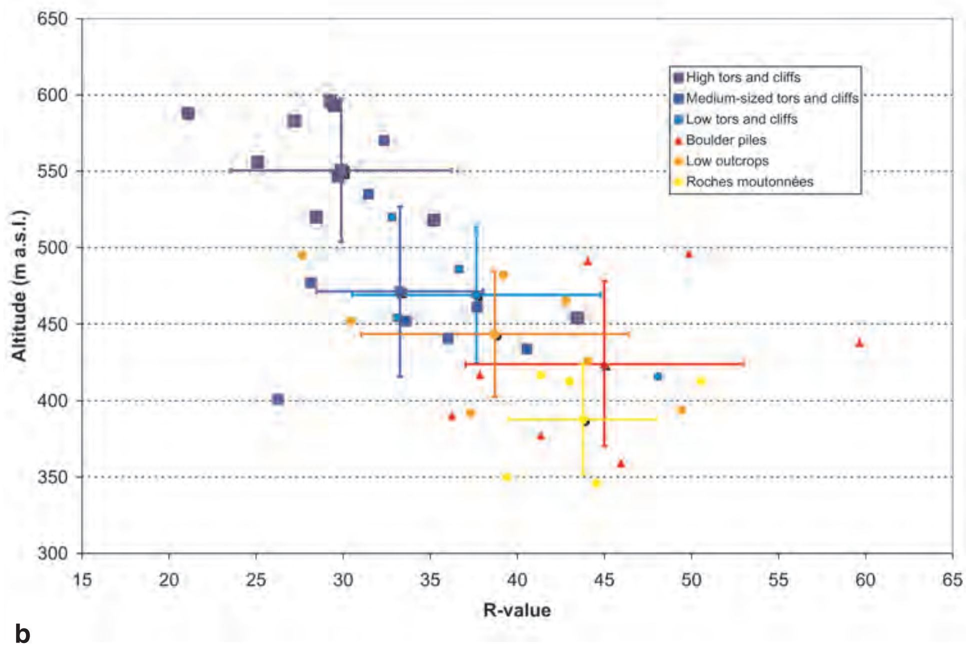
Based on this contrast the Schmidt Hammer data were divided into two groups: above (high tors) and under the potential trimline (the rest of outcrops). The histogram (Fig. 4) compares these two groups, representing the rebound values of single impacts. Only the measurements on polished surface were displayed as an example. The skewed distribution of the high tors rebound values is evident, with the highest occurrence of relatively low value of 27. By contrast, the group of outcrops under the potential trimline has the normal distribution and the most frequent values are markedly higher: 35–43. This marked difference in the data distribution bears evidence of the weathering contrast between high tors and the other outcrops.

Single rebound values (not calculated R-values) are showed. In total: 1000 impacts.

The study of Ballantyne et al. (1998) proved very similar results from the Schmidt Hammer measurements in Scotland. The characteristics of histograms (data distribution, R-value difference) for group of measurements

Fig. 3. Schmidt Hammer R values and outcrop types.
a – natural surface,
b – polished surface.





above and under the trimline in Scotland are almost identical with these for high tors and other outcrops in the Jizera Mts. On the basis of the Schmidt Hammer results on natural surfaces only, the trimline situated between high tors and the other outcrops was already suggested in the earlier paper (Janásková – Koubová 2007).

The Schmidt Hammer data evaluation in the profile lines across the slope

For Schmidt Hammer data evaluation on each profile line the graphs on Fig. 5a–f were used. The weathering limit was delimited in the altitude where the Schmidt Hammer R-values showed an abrupt change of general trend. The resulting limits are represented in the Table 2.

The Schmidt Hammer data are a good indicator of the ice sheet limit, if the rebound values on the profile line prove some contrast in R-values above and under some altitude. Such a contrast is evident on the Fig. 5b (polished surface) or 5e (natural surface).

However, in some cases the graph interpretation was difficult or even impossible because of two reasons.

Table 2. Altitudes of weathering limit obtained from R-value data in profile lines

Profile line number	**1**	**2**	**3**	**4**	**5**	**6**
polished surface	500	475	510	490	552	440
natural surface	–	500	–	460	436	440

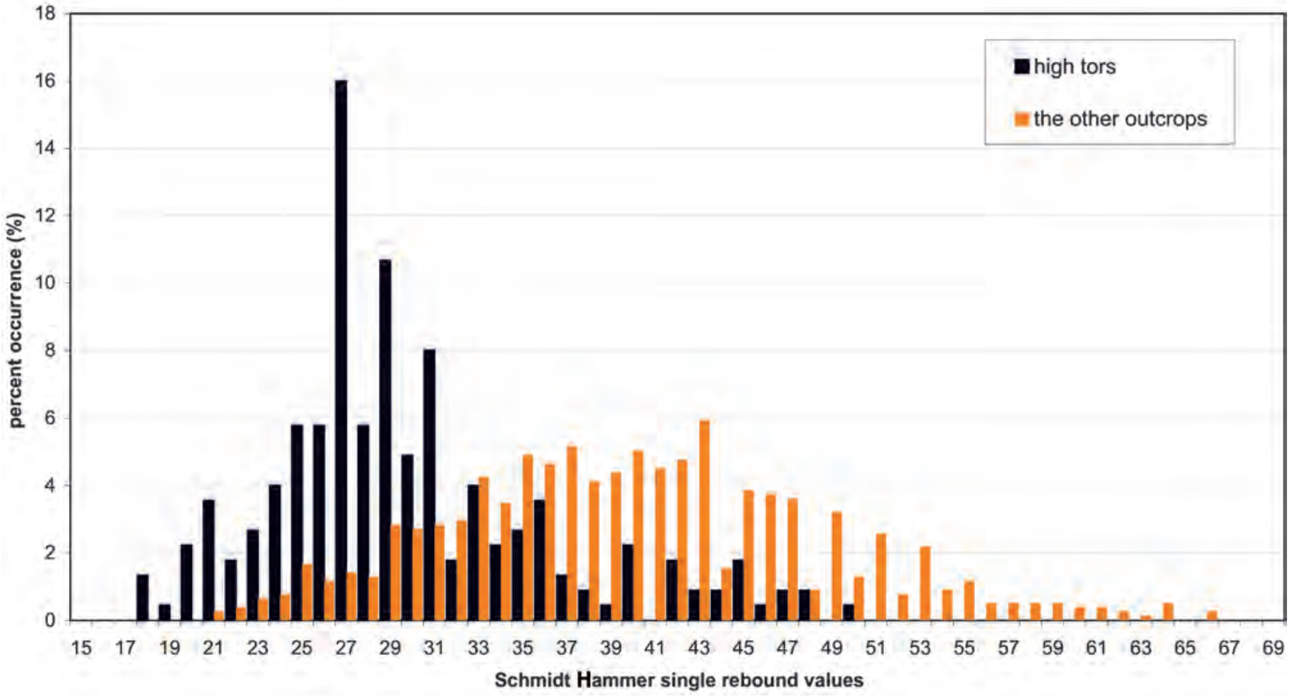


Fig. 4. Frequency distributions of Schmidt Hammer single rebound values for high tors and the rest of outcrops.

Firstly, the number of study points for Schmidt Hammer measurements on one profile was too small to prove a reliable result. The method of Schmidt Hammer measurements does not prove accurate definite data and always needs statistic evaluation and interpretation. The resulting Schmidt Hammer values obtained by fieldwork are always a bit scattered and therefore the small number of study sites can cause that the data distribution is not typical. Secondly, the obtained rebound values can contain errors. The errors can be due to the local properties of the measured outcrop such as small fractures under the surface, which cannot be observed and avoided. In the case of profiles, the errors are not eliminated by the larger number of measurements and can be misleading.

The rock outcrop morphology mapping

The total of 171 outcrops were mapped and measured on the profile lines across the slope. Another 92 outcrops were already mapped during the preceding research (Janásková – Koubová 2007). In sum it makes 263 mapped outcrops, which are represented on the Fig. 6.

The most frequent type of outcrop is a boulder pile (31%). All categories of tors, low outcrops and roches moutonnées have similar share between 10 and 16%. The frequency of cliffs is below 3% and therefore they are added to the tors of identical height in some of the following graphs.

First, the obtained data were analyzed altogether in order to find out how the types of outcrops are distributed at various altitudes. As the graph (Fig. 7) represents, according to the median the roches moutonnées are situated at the lowest altitude. Low outcrops, boulder piles and low tors together with low cliffs have almost identical median in altitude of 433–441 m a.s.l. An altitude-median of medium-sized tors and cliffs is almost 50 m higher. The high tors and cliffs are most often situated above 500 m a.s.l., their median altitude is 552 m.

Red lines represent median, rectangles represent quartiles and lines the whole range of occurrence.

Although all the outcrops situated on studied profile lines were mapped, they represent only a sample of all the outcrops on the slope. This sample is fully representative within the altitude of 350 to 600 m a.s.l. As the research was not focused on higher altitudes, the number of outcrops measured above 600 m is low and unrepresentative. Certainly the altitude-medians of some outcrop types could be different within the higher altitude range. However, the result would remain the same: across the slope the morphology of outcrops changes. The roches moutonnées are typically situated at the foothill and in the lowest part of the slope, whereas higher on the slope the low outcrops and low tors occur and their height increases with the altitude. On the other hand, the boulder piles are quite frequent throughout the whole slope.

Figure 8 represents the distribution of outcrop types within various altitude ranges. The most striking is the abrupt change of the outcrop types abundance at the altitude of 500 m a.s.l. The roches moutonnées occur below 500 m only. The compact outcrops with small

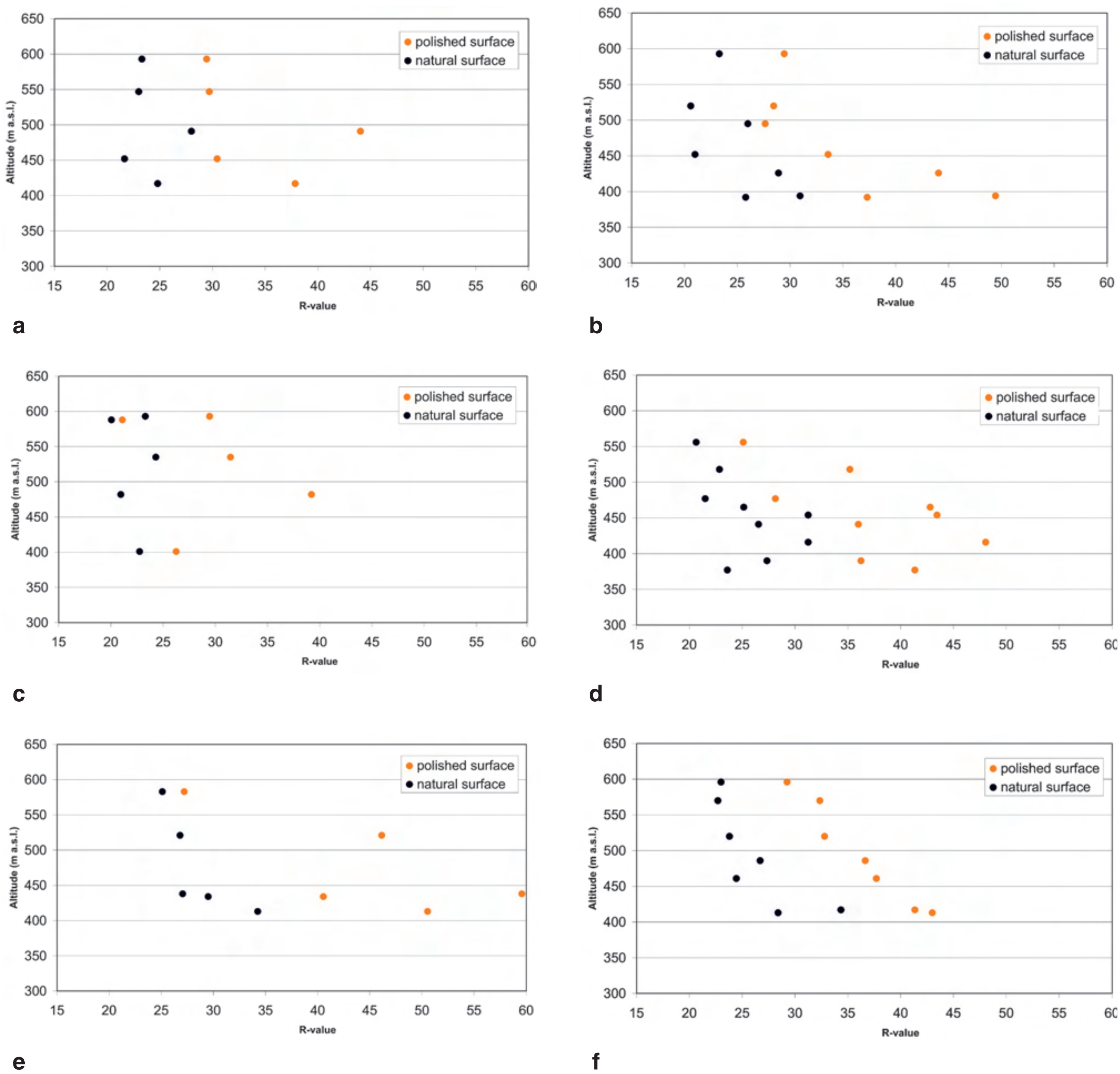


Fig. 5. Schmidt Hammer R-values on profile lines.

height (roches moutonnées, low outcrops, low tors and low cliffs) comprise more than 40% of all outcrops below 500 m. In contrast, above this altitude, the abundance of outcrops with height up to 3 m drops below 10% while the abundance of tors higher than 3 m rises at 50% or more. The altitude of this abrupt change (500 m) is approximate only, since was delimited as the interval limit. The specific altitude of change in outcrop types can differ in terrain.

The abrupt change in the character of outcrops from prevailing outcrops of low height to high tors was analyzed separately on each profile. The location of the outcrops in profiles is represented on Fig. 9. The following Table 3 summarizes the altitudes, where the prevailing character of outcrop types changes on each profile line:

Table 3. Altitudes of weathering limit deduced from change of the prevailing outcrop type

Profile line number	1	2	3	4	5	6
Altitude (m a.s.l.)	480	490	500	480	450	550

Blockfields mapping

The lower limit of blockfields was mapped on every profile line. The blockfields spread out as a continuous cover from the highest point of profile line as far as to the altitude of 440–490 m on all the profiles. Note the short range of altitudes: all the blockfields have their low limits within similar altitude. Only the profile 4 differs,

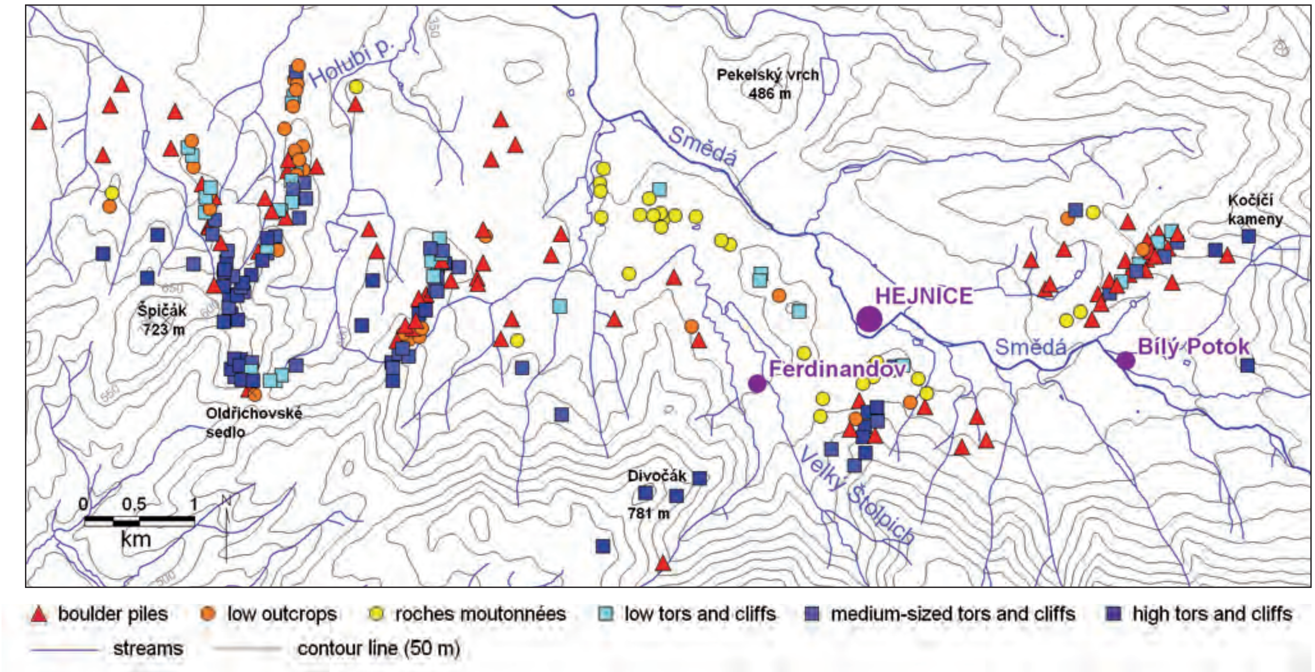


Fig. 6. Mapped outcrops and their types.

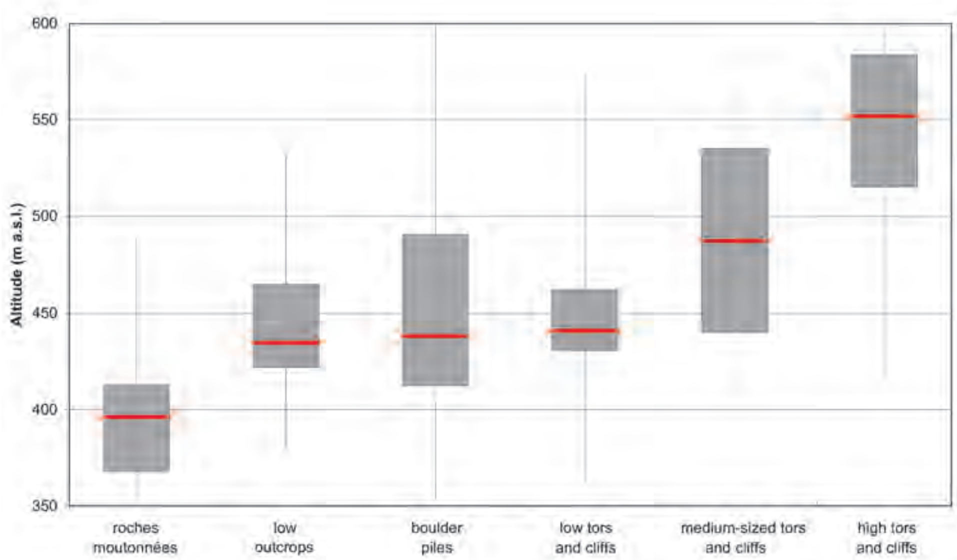


Fig. 7. Occurrence of outcrop types throughout the slope.

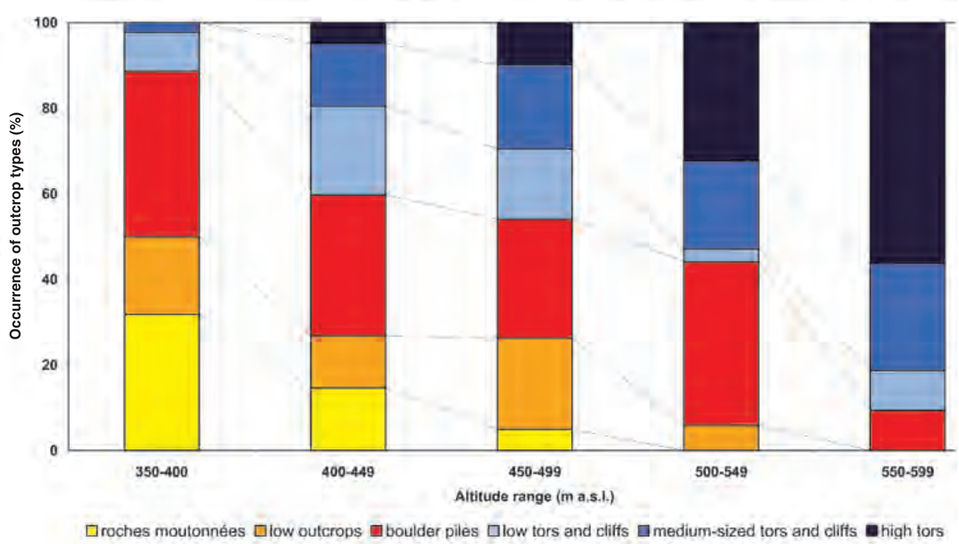


Fig. 8. Occurrence of outcrop types in various altitudes.

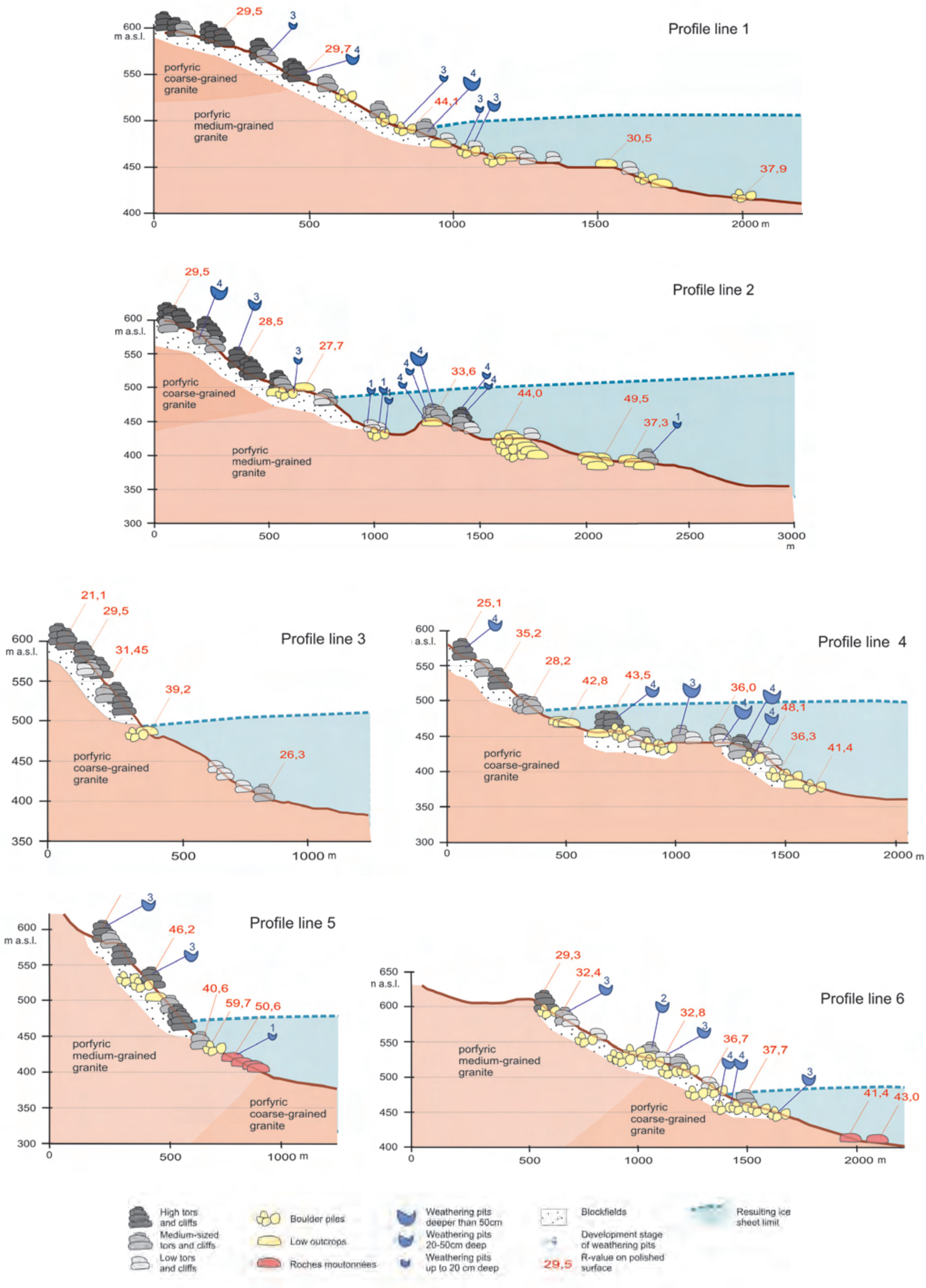


Fig. 9. Schemes of profile lines (exaggerated 3×).

Table 4. Altitudes of weathering limit educed from the lower limit of blockfields

Profile line number	1	2	3	4	5	6
Altitude (m a.s.l.)	475	440	490	480	450	440

as the blockfields cover the slope in lower altitudes as well (460–440 and 440–380 m).

The extent of blockfields is illustrated on Fig. 9. Following Table 4 summarizes the lower limit of blockfields representing the weathering limit on each profile.

The low limits of blockfields can differ from the glacial limit, as the mass-movement processes such as solifluction and debris flow could have transported debris downslope after deglaciation (Ballantyne et al. 1998). Therefore the proper trimline may be situated rather higher than the low limit of blockfields.

Another problem in data interpretation arise from difficulties in mapping the low limit of blockfields. Rapp and Rudberg (1960 in Dahl 1966, p. 58) warned that the blockfield boundary is often very diffuse and difficult to follow. Therefore the resulting altitudes in each profile line must be considered as rough with regards to accuracy rate of this method.

Weathering pits

Among of all 171 outcrops mapped on profile lines 54 have one or more weathering pits. In sum 87 weathering pits were mapped and measured. Plenty of them retain water for long periods and can be according to Hall and Phillips (2006) regarded as active. On the other side, there are also many displaced boulders with fossil weathering pits in unoriginal position.

Weathering pits occur throughout the whole slope, on almost all types of outcrops – tors of all sizes, low outcrops, boulder piles and even roches moutonnées. Figure 10 represents the percentage of outcrops with weathering pits and the five development stages of pits were distinguished as well. Approximately 15–30% of outcrops have some weathering pit. The abundance of outcrops with pits is the lowest below 400 m a.s.l. Nevertheless, above the altitude of about 500 m (which is the limit where much higher tors occur than below), the amount of weathering pits is misrepresented, as these are usually situated too high to be accessed or even observed.

The development stages of weathering pits prove to be independent on both altitude (correlation coefficient = –0.08) and outcrop type. Weathering pits up to the third development stage were observed on roches moutonnées, pits up to the fourth stage occur on low outcrops and pits of all stages occur on boulder piles and tors.

The depth of weathering pits is represented on the graph (Fig. 11). The variety of depth throughout the whole slope is obvious. Weathering pits deeper than 50 cm are frequent even below the altitude of 450 m a.s.l. The correlation coefficient of 0.14 also confirms the independence of altitude and weathering pit depth.

To verify a correlation of altitude and weathering pit size as well, the approximate volume of pits was calculated as a product of length, width and depth. The correlation coefficient of –0.20 (negative!) confirms the independence of pit volume on altitude.

The development stage as well as depth and position in profile line is also represented on Fig. 9.

According to the approach of Hall and Phillips (2006), who used weathering pits as an indicator of relative age of outcrops, younger outcrops are supposed to have flatter, smaller or less developed pits. However, in the

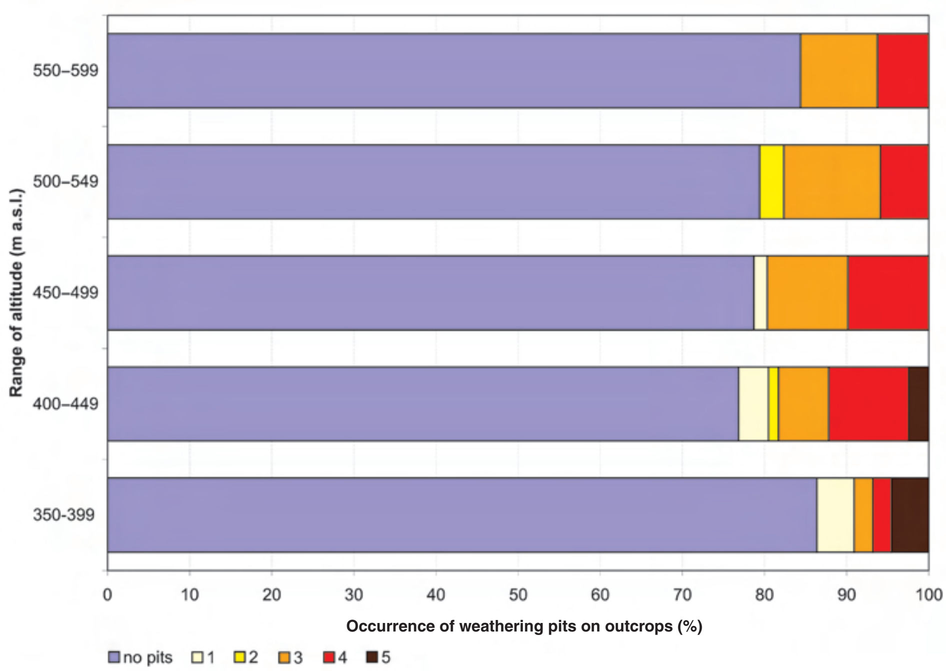
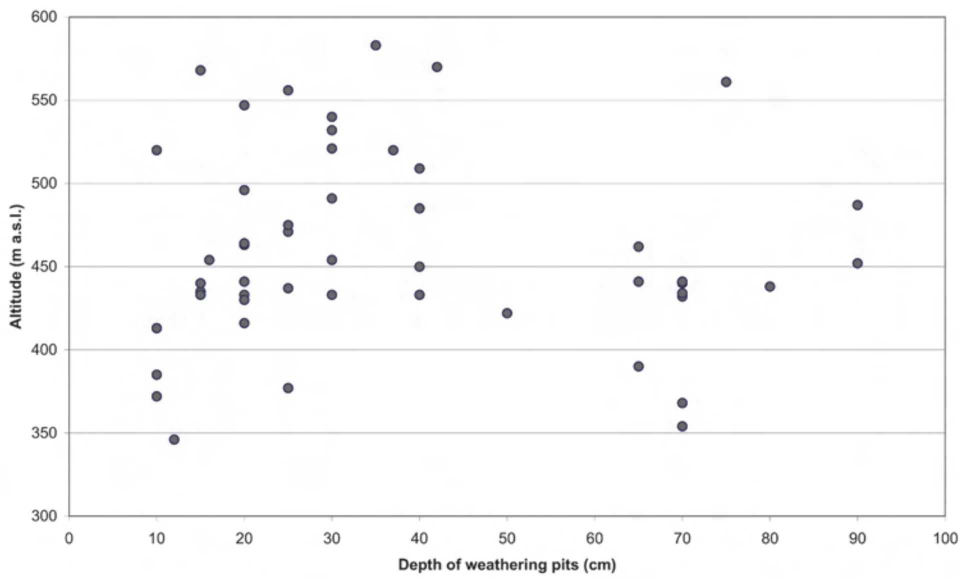


Fig. 10. Occurrence of weathering pits with various development stages (development stages 1–5 according to Votýpka 1964).

Fig. 11. The depth of weathering pits and altitude.



Jizera Mts. weathering pits of all stages and various depths occur throughout the whole slope. Not any contrast, abrupt change or dependence on glacier erosion or altitude in the distribution and character of weathering pits was proved.

No contrast or abrupt change was found in weathering pits character and distribution throughout the slope. Neither their dependence on glacial erosion or even altitude was proved. Consequently, weathering pits could not be used as an indicator of glacial erosion in this study.

Discussion

The results of all the techniques of data evaluation were used for trimline determination and are listed in Table 5. Some of them allowed determining the altitude of weathering limit for all profile lines together only. The final altitude of glacial trimline was constructed in virtue of the resulting altitudes, excluding the extreme ones or anomalies. The trimline altitude was extrapolated from profiles to whole slope and is mapped on the Fig. 12.

The variability of resulting altitudes in profile lines is 20 m only. The highest altitude resulted from the profile 3, which includes the highest location of proved glacial extent – Oldřichov Col (478 m). Furthermore, the altitude of weathering limit decreases eastwards, what greatly corresponds with the supposed ice movement. After reaching the valley of the Smědá river the ice sheet was likely to lose the thickness and erosive force. Nevertheless, although the resulting altitudes well agree with present knowledge or conceptions, these interpretations go rather beyond the accuracy of the weathering limit determining, as written further.

None of the methods used is fully accurate or reliable. Considering the fact that trimline may be diffuse and

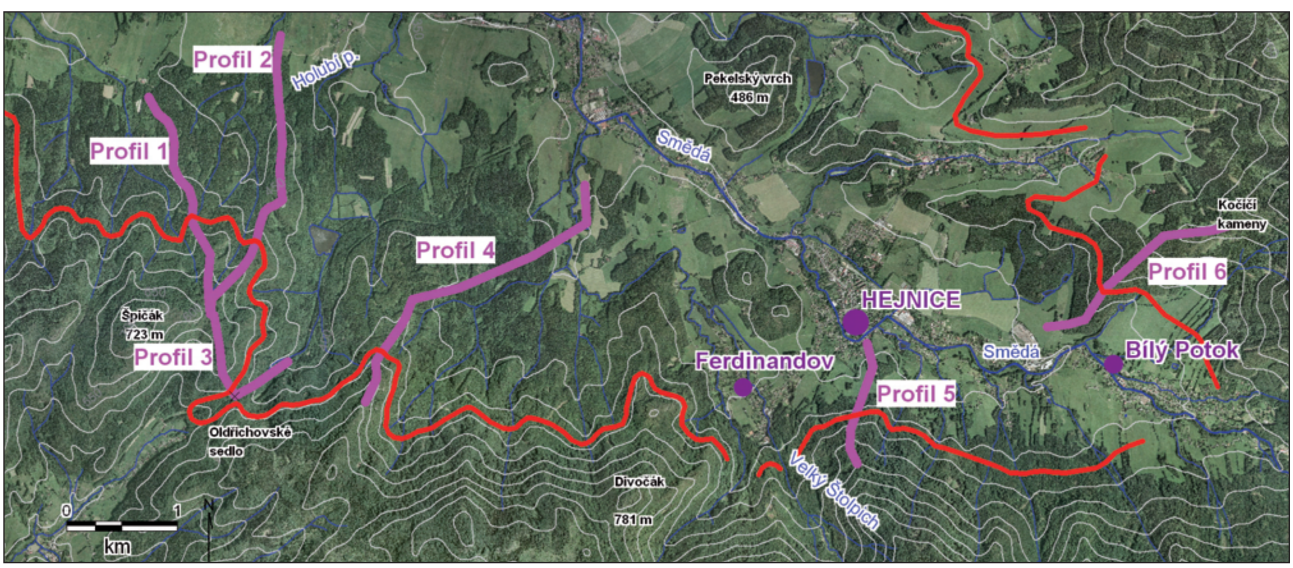


Fig. 12. Trimline extrapolated from profile lines results.

Table 5. Summary of weathering limit altitudes obtained by used methods

Methods	Altitude of weathering limit (m a.s.l.)					
	profile 1	profile 2	profile 3	profile 4	profile 5	profile 6
R-value median contrast, polished surface	470					
R-value median contrast, natural surface	450					
R-value range abrupt change, polished surface	490					
R-value range abrupt change, polished surface	450–490					
Comparison of R-values and outcrops morphology	~ 500					
R-value abrupt change on profiles, polished surface	500	475	510	490	552	440
R-value abrupt change on profiles, natural surface	–	500	–	460	436	440
Change of the prevailing outcrop type – profiles	480	490	500	480	450	550
Change of the prevailing outcrop type	~ 500					
Blockfields low limit	475	440	490	480	450	440
Weathering pits: change in depth or development stage	–					
Median	480	483	490	480	470	470
Range	450–500	440–500	450–510	450–500	436–500	440–550
Resulting altitude of weathering limit (trimline)	**480**	**480**	**490**	**480**	**470**	**470**

unclear, some questions doubting the suitability of used methods for this study area arise. According to Thorp (in Ballantyne et al. 1998, p. 1156), the clarity of trimline depends on the effectiveness of glacial erosion, the susceptibility of ice-scoured terrain to frost weathering and the efficacy of mass-movement processes after deglaciation.

In particular the effectiveness of glacial erosion in the marginal part of ice sheet has been broadly discussed in Czech Republic. Some authors described exaration plains in the northern slope of the Jizera Mts. (Králík 1989, Macoun – Králík 1995) or typically modeled roches moutonnées in both Northern Bohemia and Northern Moravia (Králík 1989, Macoun – Králík 1995, Prosová 1983, Demek 1976, Janásková 2009). By contrast, some authors denied the glacial genesis of the plains (Czudek 2005) and roches moutonnées (Czudek 2005, Vídeňský et al. 2007). These dome-shaped elevations they regard as remnants of preglacial weathering, most of which have been not significantly modified by glacial erosion. According to Czudek (2005), glacial impact in Czech glaciated areas was small: the ice-sheet removed older products of weathering, but did not widely affect the bedrock.

This is not rare even in the areas glaciated during the last glaciation. Lowe and Walker (1997) claim that landforms that developed under a previous climatic regime often survive the glaciation, although sometimes in a much modified form. Not only the roches moutonnées are described as just slightly affected (Lindstrom 1988), but also blockfields (Fjellanger et al. 2006) and even tors (Sugden – Watts 1977, Stroeven et al. 2002, Hättestrand – Stroeven 2002) can survive glaciations.

The concepts about inefficiency of glacial erosion and applicability of trimline methods do not necessarily contradict each other. Although the landforms can survive glaciation, they are usually modified, for example the uppermost part of tors is removed (Stroeven et al. 2002). In conclusion, even small efficiency of erosion can be sufficient to cause the differences in relief above and under the trimline.

Another objection against the results of trimline methods is the period of time passed since glaciation, which was long enough for trimline to be overprinted by younger processes. This is a serious problem when using the trimline method in the northern slope of the Jizera Mts., as the time period passed since deglaciation is long and the overprinting extensive.

The problems with overprinting affected all the methods used in this study. The Schmidt Hammer measurements are doubtful for determining the long-period evolution of landforms, since the resolution of Schmidt Hammer dating is still obscure. Authors usually use this method for relative dating of the upper Pleistocene landforms (Sjoberg 1990, Lindstrom 1991, Anderson et al. 1998, Ballantyne 1997, Ballantyne et al. 1998, McCarroll – Ballantyne 2000). Furthermore, both the morphology of outcrops and blockfields was affected by long-term periglacial weathering. Blockfields can be also modified by mass-movement, and even their evolution from postglacial weathering products is known (Dahl 1966).

Weathering pits proved to be unusable for trimline determination in this study area. This is the consequence of either long time passed or the glacial erosion inefficiency, which enabled surviving of pits and their further development after deglaciation. Supposedly the time needed for weathering pits development is much shorter than the time passed since the glaciation. Very probable is also the combination of both these reasons.

The reason against the total overprinting is the uniform altitude of weathering limit obtained by all the methods and techniques of data evaluation. Table 5 sums up the total of 10 techniques of weathering limit determining and all of them proved very similar altitude of 450–500 m a.s.l.

There is also a possibility that the weathering limit is a product of progressively greater rock breakdown at higher altitude. This can be rebutted by the fact of abrupt change in obtained data. The methods were focused on looking for contrasts, not just continuous change, which would be the consequence of different climatic conditions throughout the slope.

Next problem that arose using the trimline methods is their relative inaccuracy resulting from their limitations or their application in this study area. This is the case of mapping blockfields boundary, which is often difficult to follow (Rapp and Rudberg in Dahl 1966, p. 58). For another instance, the Schmidt Hammer impacts show considerable variability, which is common according to Goudie (2006), but it causes difficulties. The variability of single impacts on each study point was much smaller after surface polishing, but still remained sufficient to confuse the interpretation. Schmidt Hammer data proved more reliable results when educed from number of R-values. Some of the Schmidt Hammer profile lines were difficult to interpret or even did not bring any results because of small number of measured sites.

To sum up, the resulting altitude of trimline in Table 5 was educed on the basis of Schmidt Hammer rebound measurements on polished and natural surfaces, the rock outcrop morphology mapping and the low limits of blockfields. Dealing with this altitude it is necessary to be aware of the limitations of methods used in this study. Not only the methods do not bring too accurate results, but also the altitude of the ice sheet surface in its marginal oscillation zone was not unchanging, but rather extremely dynamic. Therefore, the resulting altitude of trimline must be regarded rather as a zone ranging circa ± 20 m from the altitudes stated in Table 5.

Conclusions

The aim of this research was to determine the ice sheet limit in the northern slope of the Jizera Mts. using the trimline methods that proved good abroad.

- The methods of Schmidt Hammer rebound measurements on polished and natural surfaces, the rock outcrop morphology mapping and mapping of the low limits of blockfields brought good results for glacial limit determination.
- The glacial limit was delimited using the combination of these methods in the altitude of 470–490 m a.s.l. and is represented on Fig. 12 and 9.
- With respect to the limitations and accuracy of the methods, the resulting trimline must be regarded rather as a zone ranging about ± 20 m from the resulting altitudes.
- The method of weathering pits mapping and measurements proved unusable as an indicator of glacial erosion in the northern slope of the Jizera Mts. The variety of depth and development stages of weathering pits was obvious throughout the whole slope and no abrupt change was found. This is the consequence of either long time passed since the glaciation or the relative inefficiency of glacial erosion. Most probable was the combination of both.
- Surface polishing by an electric grinder before Schmidt Hammer measurements was found very helpful, since it caused not only better data accuracy, but also a substantial increase in R-value range. This increase of data range emphasized the contrast between more and less weathered surface.

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