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Dating of recent avalanche events in the Eastern High Sudetes, Czech Republic

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A B S T R A C T

This article deals with recent avalanche events dated by the dendrogeomorphic method and their verification. The research was focused on two active mid-mountain avalanche sites – the Sněžná kotlina Hollow and the Morava Hollow in the Eastern High Sudetes. A total of 96 trees were analysed and eight highly probable avalanches were identified since 1924 and 1935, respectively. The avalanche events were verified using historical aerial photographs, meteorological data and different historical sources (i.e. local newspapers, historic photographs, etc.). Avalanches are more frequent in the Sněžná kotlina Hollow (avalanche years: 1984, 1993, 2004, 2005, 2007, 2008) than in the Morava Hollow (avalanche years: 1942, 1999). Most avalanche events correspond with heavy snowfall events or high temperature events during February and March. There are significant differences in the frequency of avalanches between the two study sites that are reflected in the morphology of the avalanche paths under study. The more active avalanche path has a more ragged surface and includes a typical avalanche gully. The results of the verification support the use of the dendrogeomorphic method because the potential avalanche events were clearly confirmed.

1. Introduction

Snow avalanches are important phenomena in mountain ranges all around the world, when the alpine regions are the most discussed. Nevertheless, the snow cover in mid-mountains is also important factor, which provides similar processes as in the alpine areas. Avalanches in mid-mountain ranges are an important factor in (i) geomorphic processes, (ii) ecology, (iii) forestry and (iv) natural hazard management at different timescales.

(i) Full-depth avalanches usually affect the surface of avalanche paths (Luckman, 1977; Decaulne and Saemundsson, 2006). The volume of material transported by avalanches in the High Sudetes can exceed 1000 m^3 (Kociánová et al., 2013), which is a relatively large value considering the size of the mountain range with highest altitudes around 1300 m a.s.l. Thus, even in mid-mountain environments, avalanches of different magnitude and frequency play an important role in the surface remodelling of their paths, and also prepare slopes for other geomorphologic phenomena such as solifluction and debris flows (Rapp, 1960; Křížek et al., 2010). Seasons with avalanche activity can be also related to climatic influence on freeze-thaw and nivation activity in nearby area (Rapp and Nyberg, 1988).

(ii) The ecological function of full-depth avalanches is indispensable for the biodiversity of hollows where avalanches occur. Avalanche activity locally depresses the position of the alpine tree line by removing vegetation from avalanche paths during strong avalanche events (Treml and Banaš, 2000; Teich et al., 2012). Corridors created by avalanche activity (Butler, 2001) and the transportation and accumulation of organic material influenced by avalanches create specific avalanche path biotopes with the presence of many species (Jeník, 1961; Rixen et al., 2007). Periodic avalanche activity maintains the most valuable botanical locality in the High Sudetes – the Velká kotlina Hollow (Jeník et al., 1980).

(iii) Strong avalanche events can damage large areas of forest (e.g. Rayback, 1998; Bebi et al., 2009; Teich et al., 2012; Baugher and Birkeland, 2014). In the High Sudetes Mts., powder avalanches can have a very strong impact force of about 1000 kN/m^2 (Vrba and Spusta, 1975) and have repeatedly caused forest damage (Sokol, 1965; Kociánová et al., 2013).

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(iv) Avalanches can destroy property and endanger human lives even in mid-mountains. In the Western Sudetes Mts., more than one hundred victims have been reported since 1655 (Kociánová et al., 2013). With the rising popularity of winter sports, the number of casualties could increase also in the Eastern High Sudetes, where six victims have been reported since 1934 (Navrátil, 2016).

Dendrogeomorphic analysis is a very useful tool for dating avalanche events using the basic 'event-response' principle (Schroder, 1980). The postulate is that trees growing within or on the borders of avalanche paths, with some probability, get damaged during avalanche events (e.g. Butler and Sawyer, 2008; Corona et al., 2010, 2012; Stoffel et al., 2013; Tumajer and Treml, 2013; Stoffel and Corona, 2014; Pop et al., 2016). The exact dendrogeomorphic algorithms used (calculation of the avalanche index and the threshold value of the index) are highly variable and depend on many specific local features of each avalanche environment such as the impact of wind or slow slope processes over the course of the year (Butler et al., 1987; Chiroiu et al., 2015), so the results can be quite different when different approaches are taken. Thus, because of this potential inaccuracy, results of the dendrogeomorphic method should be verified with other sources (Martinelli and Charles, 1999; Corona et al., 2012; Tumajer and Treml, 2015; Giacona et al., 2017).

The aims of this paper are to determine the frequency of recent avalanche activity in a mid-mountain range represented by the Eastern High Sudetes based on the dendrogeomorphic method, to verify its results using monitoring of changes in vegetation cover visible on historical aerial photographs, written sources (i.e. newspapers, local books, etc.) containing records of avalanche events from different avalanche paths in the same mountain range and meteorological data from nearby meteorological stations. There has been no cumulative monitoring of recent avalanche activity in the Eastern High Sudetes. There is also no evidence concerning geomorphic features of avalanche paths in this area or their possible relationship to current avalanche activity.

2. Study area

The Eastern High Sudetes are situated in the north-eastern part of the Bohemian massif near the border between the Czech Republic and Poland (Fig. 1). This mountain range is composed of two parts, the Hrubý Jeseník Mts. (highest peak Mt. Praděd, 1492 m a.s.l.) and the Králický Sněžník Mts. (highest peak Mt. Králický Sněžník, 1424 m a.s.l.). The Eastern High Sudetes are a Variscian fault-block mountain range composed of metamorphic rocks (gneisses, phyllites, mica schists and quartzites) (Chlupáč et al., 2011). Both parts of the Eastern High Sudetes reach above the alpine timberline, which lies at an average elevation of 1310 m a.s.l. (Treml and Banaš, 2000; Treml et al., 2008). The slopes of the mountains are mostly forested by *Picea abies*. The 1961–1990 mean annual air temperature on Mt. Praděd was +1.7 °C (Coufal et al., 1992). The 1947–1985 mean annual precipitation was 1231 mm (data of the Jeseníky Landscape Protection Area authority). Snowfall may occur in the highest parts of the mountain range at any time during the year. The 1947–1985 mean number of days with snow cover was 171 per year (data of the Jeseníky Protected Landscape Area authority). The 1947–1985 mean annual maximum snow depth was 195 cm on Mt. Praděd, and the greatest snow depth occurred in early March (data of the Jeseníky Protected Landscape Area authority). The landscape of the Hrubý Jeseník Mts. and the Králický Sněžník Mts. is characterized by deep valleys with steep slopes and summit plateaus. Deep valleys with steep slopes

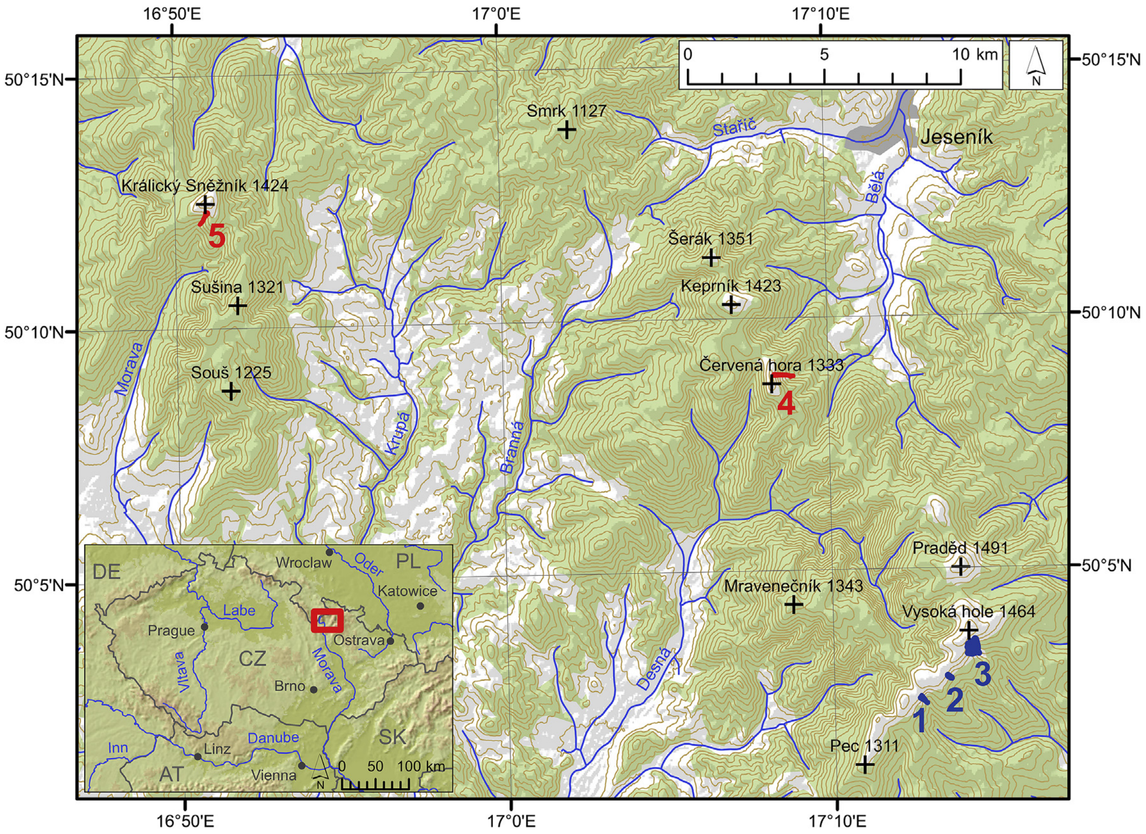

Fig. 1. Avalanche paths of the Eastern High Sudetes: 1-Malá Kotlina Hollow, 2-Mezikotlí Hollow, 3-Velká kotlina Hollow, 4-Sněžná kotlina Hollow, 5-Morava Hollow.

were remodelled by fluvial erosion and nivation (Křížek et al., 2010), and a several metres thick weathered mantle creates favourable conditions for slope phenomena (such as debris flows and avalanches). Debris flows occurred where the products of weathering were saturated with water from melting snow or rainfall, e.g. in 1893, 1903, 1907, 1921, 1938, 1940, 1951, 1965, 1968, 1991, 1994, 1997 and 2004 (Křížek, 2016 and references therein).

Kříž (1995) described a total of 22 avalanche paths in eight areas in the Eastern High Sudetes, but the current number is lower – about 16 avalanche paths in six areas (data of the Mountain Rescue Jeseníky; Fig. 1). This is because slopes prone to avalanches have been afforested or have overgrown with dwarf pine or trees, which prevent avalanches, for example in the Hučivá Desná valley or Borový důl valley (Sokol, 1965; Navrátil, 2016). All of the avalanche areas are located in upper sections of fluvial valleys, except one which is situated in the cirque of the Velká kotlina Valley (Křížek et al., 2012). Other recent avalanche areas are situated in the Malá kotlina Hollow, the Mezikotlí Hollow, the Sněžná kotlina Hollow and the Morava Hollow (Fig. 2). The Sněžná kotlina Hollow avalanche path (1290–939 m a.s.l.) is located on the eastern (leeward) slope of Mt. Červená hora (1333 m a.s.l.) in the central part of the Hrubý Jeseník Mts. The avalanche path of The Morava

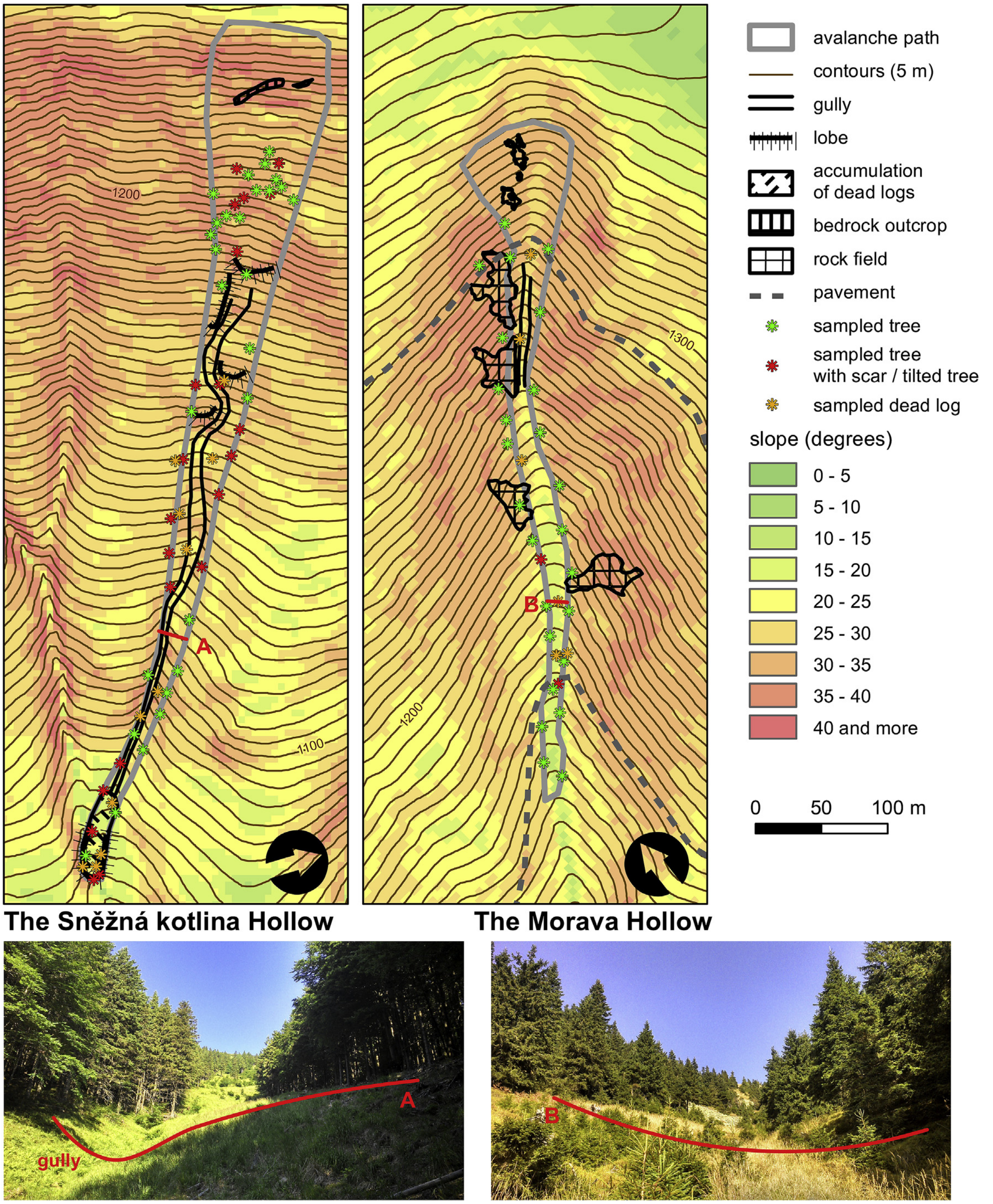

Fig. 2. Detailed situation of both studied paths with position of analysed trees.

Hollow (1345–1141 m a.s.l.) is situated on the southern slope of Mt. Králický Sněžník (1424 m a.s.l.) (Fig. 1).

3. Methods

3.1. Sampling and dendrogeomorphic approaches

Samples for dendrogeomorphic analysis were taken from 50 living trees in the avalanche path of the Sněžná kotlina Hollow and 27 living trees in the avalanche path of the Morava Hollow using a Pressler increment borer. These two avalanche paths reach down into the closed forest, so they were selected for dendrogeomorphic sampling. In line with other dendrogeomorphic avalanche studies (e. g. Chiroiu et al., 2015; Tumajer and Treml, 2015; Pop et al., 2016), sampled trees were spatially distributed within or symmetrically on both sides of the avalanche path to capture all possible directions of avalanche movement in the path (see Fig. 2 and Table 1). Three increment cores were taken from each living tree in three directions – upslope, downslope and along the contour (sensu Corona et al., 2010; Tumajer and Treml, 2015). The stem height of cores was most often about 130 cm (Reardon et al., 2008). Trees showing visible damage (i.e. scars) were chosen preferentially and extra cores from the callus tissue overgrowing scars were taken to date the scars (Stoffel and Bollschweiler, 2008). In addition, eleven trunk cross-sections in the avalanche path of the Sněžná kotlina Hollow and eight cross-sections in the avalanche path of the Morava Hollow on Mt. Králický Sněžník were taken from dead downslope-oriented logs located in these paths (sensu Reardon et al., 2008). All samples (i.e. 3 cores × 77 sampled trees + 19 cross-sections = total 250 samples from both paths) were taken during autumn 2013 and summer 2014. The GPS coordinates of every sampled tree or log were recorded (Fig. 2, Table 1).

Each dendrogeomorphic core sample was measured and analysed using TimeTable and PAST 4 software (SCIEM, 2009), and traumatic resin ducts were noted if they were present in the measured tree rings. Every dataset was compared with a standard reference chronology from a nearby area (Ponocná et al., 2016) to detect missing growth rings and to eliminate possible climatic triggers of growth changes. Cross-sections from logs in accumulation areas were cross-dated with the reference chronology. The last ring of these logs was considered the last growing season before the potential avalanche event. The following markers from living trees were taken into account as potential avalanche indicators: abrupt growth changes, ring eccentricity, presence of traumatic resin ducts and presence of scars.

Negative and positive abrupt growth changes were detected using the following formula (sensu Tumajer, 2013):

$$I_{c(t)} = \frac{R_t + R_{t+1} + R_{t+2}}{R_{t-1} + R_{t-2} + R_{t-3}} - 1 \;\; ; \quad \forall I_c \notin (-0,35; 0,6) \rightarrow \text{“abrupt growth change”},$$

where $I_{c(t)}$ is the growth change index in year t and R is the width of the exact ring. Only the first year when the index indicated an abrupt growth change was taken into account if other significant values followed.

In accordance with Schweingruber (1996), the eccentricity index was defined as:

$$I_{ecc(t)} = \frac{R_{d(t)}}{R_{u(t)}},$$

where $I_{ecc(t)}$ is the eccentricity index in the year t, $R_{d(t)}$ is the width of the downslope-oriented tree ring and $R_{u(t)}$ is the width of the upslope-oriented tree ring, both in year t. In accordance with Tumajer (2013), the eccentricity index was defined as:

$$I_{eccx(t)} = \frac{\frac{I_{ecc(t)} + I_{ecc(t+1)} + I_{ecc(t+2)}}{3}}{\frac{I_{ecc(t-3)} + I_{ecc(t-2)} + I_{ecc(t-1)}}{3}},$$

where $I_{eccx(t)}$ is the eccentricity change in year t and I_{ecc} is the abovementioned eccentricity index. The $I_{eccx(t)}$ index value was considered significant when it exceeded 1.45, which means a 45% increase of eccentricity and formation of reaction wood. As in the case of growth changes, where more significant index values followed in subsequent years, only the first year was taken into account.

The presence of traumatic resin ducts was recorded during the measurement of tree ring widths using PAST 4 (SCIEM, 2009), TimeTable and a binocular magnifier. Only traumatic resin ducts which occupied the majority of the width of the tree ring section except for latewood visible in the sample were considered significant features. When other traumatic resin ducts were present in continuous tree rings, only the first one was considered – in the same way as in the case of eccentricity and abrupt growth changes. Samples from visible scars were taken from their edges, and the number of tree rings healing each scar was counted or the last tree ring before the initiation of the scar was cross-dated with a standard reference chronology.

The weighted avalanche index approach (Kogelnig-Mayer et al., 2011) was used to determine potential avalanche seasons (years in which at least one avalanche event happened). The method considers not only the number (ratio) of growth disturbances, but also the deformation intensity. Thus, it was used in this study to underline avalanche events with strong visible impact. The index and its threshold were edited and adjusted for use in the Sudetes (see Butler et al., 1987; Tumajer and Treml, 2015). The weighted avalanche index (sensu Kogelnig-Mayer et al., 2011; modified) is defined as:

$$\begin{aligned} Wit = \Bigg[& \left(\sum_{i=1}^{n} GD_{dw(t)} \times 5 \right) + \left(\sum_{i=1}^{n} GD_{s(t)} \times 5 \right) \\ & + \left(\sum_{i=1}^{n} GD_{eccxa(t)} \times 3 \right) + \left(\sum_{i=1}^{n} GD_{eccw(t)} \times 1 \right) \\ & + \left(\sum_{i=1}^{n} GD_{c(t)} \times 1 \right) + \left(\sum_{i=1}^{n} GD_{trd(t)} \times 1 \right) \Bigg] \times \frac{\sum_{i=1}^{n} Rt}{\sum_{i=1}^{n} At}, \end{aligned}$$

where Wit is the weighted avalanche index in season t, $GD_{dw(t)}$ is the count of dead logs with the last ring before season t, $GD_{s(t)}$ is the count of scars present in season t, $GD_{eccxa(t)}$ is abrupt eccentricity change with $I_{eccx(t)} > \, = 2$ in season t, $GD_{eccxw(t)}$ is weak eccentricity change with $I_{ecx(t)} < 2$ in season t, $GD_{c(t)}$ is abrupt growth change in season t and $GD_{trd(t)}$ is the presence of traumatic resin ducts in season t. Rt represents the number of trees showing at least one of above-mentioned potential avalanche indicators in year t, and At represents all trees present in the path in year t. A year was considered a potential avalanche year if $Wit > \, = 2$ in season t. Only seasons with $At > \, = 10$ were analysed.

3.2. Verification of potential avalanche events and geomorphological mapping of selected paths

Historic aerial photographs (of the Sněžná kotlina Hollow from 1945, 1958, 1965, 1975, 1985, 1995, 2001, 2003, 2006 and 2013; of

Table 1
Overview of sampled trees in different parts of studied avalanche paths.

	number of trees/logs	number of trees with scar/tilted trees	number of dead logs
The Sněžná kotlina Hollow			
upper part widespread	23	5	0
left side	12	4	0
middle	1	1	4
right side	13	6	3
deposit zone	12	4	4
The Morava Hollow			
upper part widespread	8	0	2
left side	9	0	2
middle	3	0	3
right side	8	1	1
deposit zone	7	1	0

the Morava Hollow from 1936, 1946, 1957, 1970, 1976, 1986, 1995, 2001, 2003, 2006 and 2013) were compared to reveal visible differences in vegetation density within the avalanche paths. Differences between two historical aerial photographs in vegetation cover can constitute independent proof of avalanche events derived from the dendrogeomorphic approach because strong avalanches can remove vegetation from their path. The aerial photographs were provided by the Army Institute of Geography and Hydrometeorology, the GEODIS Brno company and the State Administration of Land Surveying and Cadastre.

Since 1990, other data were used for the validation. Meteorological data measured at the closest meteorological stations on Mt. Praděd (1990–1997) and Mt. Šerák (since 2004), were obtained from the Czech Hydrometeorological Institute. Unfortunately, there are no meteorological data between 1997 and 2004. Months including at least one day with snowfall exceeding 45 cm and months including at least one day with an average temperature above 10 °C were considered suitable for avalanche activity because most strong avalanche events in the Sudetes are caused by snowmelt and heavy snowfall (Blahůt, 2007; Kociánová et al., 2013).

Data on avalanche events anywhere in the Eastern High Sudetes since 1990 were obtained from the Jeseníky Protected Landscape Area authority, the Mountain Rescue Service and on-line newspapers. These data consisted of written evidence, photographs and information found by internet searching (for the term ávalanche') on the servers idnes.cz and alpy4000.cz (see Table 3 for details).

Detailed geomorphological mapping of both paths (Fig. 2) was carried out based on a combination of terrain GPS mapping and remote sensing data (Digital Terrain Model of the 4th Generation derived from LiDAR points with an elevational resolution of about 30 cm in a 5 × 5 m grid) provided by the State Administration of Land Surveying and Cadastre 2013.

4. Results

4.1. Dendrogeomorphology

In the Sněžná kotlina Hollow, a total of 425 markers of potential avalanche activity between 1924 and 2013 were identified. The most abundant marker was abrupt growth change followed by eccentricity changes (Table 2). The weighted-index method detected six potential avalanche years (1984, 1993, 2004, 2005, 2007 and 2008; Fig. 3) with the greatest value of the avalanche index in 2004. Thus, the average avalanche frequency in the Sněžná kotlina Hollow, based on the dendrogeomorphic approach, is one in every ca 15 years.

Table 2
Percentages of markers.

	The Sněžná kotlina Hollow	The Morava Hollow
dead logs	2,6	2,9
scars	1,9	0,4
eccentricity changes	28,2	36,0
abrupt growth changes	47,3	53,6
traumatic resin ducts	20,0	7,2

In the Morava Hollow, a total of 278 markers of potential avalanche activity between 1935 and 2013 were identified. The most abundant marker was abrupt growth change followed by eccentricity changes (Table 2). The weighted-index method detected only two potential avalanche years (1942 and 1999; Fig. 3). Thus, the average avalanche frequency in the Morava Hollow, based on the dendrogeomorphic approach, is one in every ca 40 years.

4.2. Validation data

Comparison of historical aerial photographs shows visible changes of the vegetation cover in the Sněžná kotlina Hollow (Fig. 4). Since 1945 the path became overgrown by vegetation. Removal of vegetation growing in the path is visible between 2003 and 2006, which supports the results obtained by dendrogeomorphological methods, with the greatest dendrogeomorphic Wit index in 2004. In the Morava Hollow, there are no important visible differences between historical aerial photographs (Fig. 5).

During the 1990–1997 and 2004–2013 periods, only one month with a day with snowfall over 45 cm was observed (1993). Winter months with temperatures over 10 °C were observed in 1990, 2004, 2005, 2007 and 2010. These meteorological data correspond with 4 of 5 avalanche events dated by dendrogeomorphology in the Sněžná kotlina Hollow during these periods covering climatic data (Table 3).

Seven avalanche events in other avalanche paths in the mountains were described in written and other sources: 2002, 2005, 2007, 2009, 2010, 2012 and 2015. The event in 2005 in the Malá kotlina Hollow and the event in 2007 in the Velká kotlina Hollow correspond with avalanche events dated dendrogeomorphologically in the Sněžná kotlina Hollow (Table 3).

Geomorphological mapping shows that the Sněžná kotlina Hollow has several forms which can be considered avalanche forms. The gully is over 400 m long and in some sections more than 4 m deep (Fig. 2). Four lobes are situated in the upper part of the path. On the other hand, the Morava Hollow has a less ragged surface with a very short and shallow gully (Fig. 2).

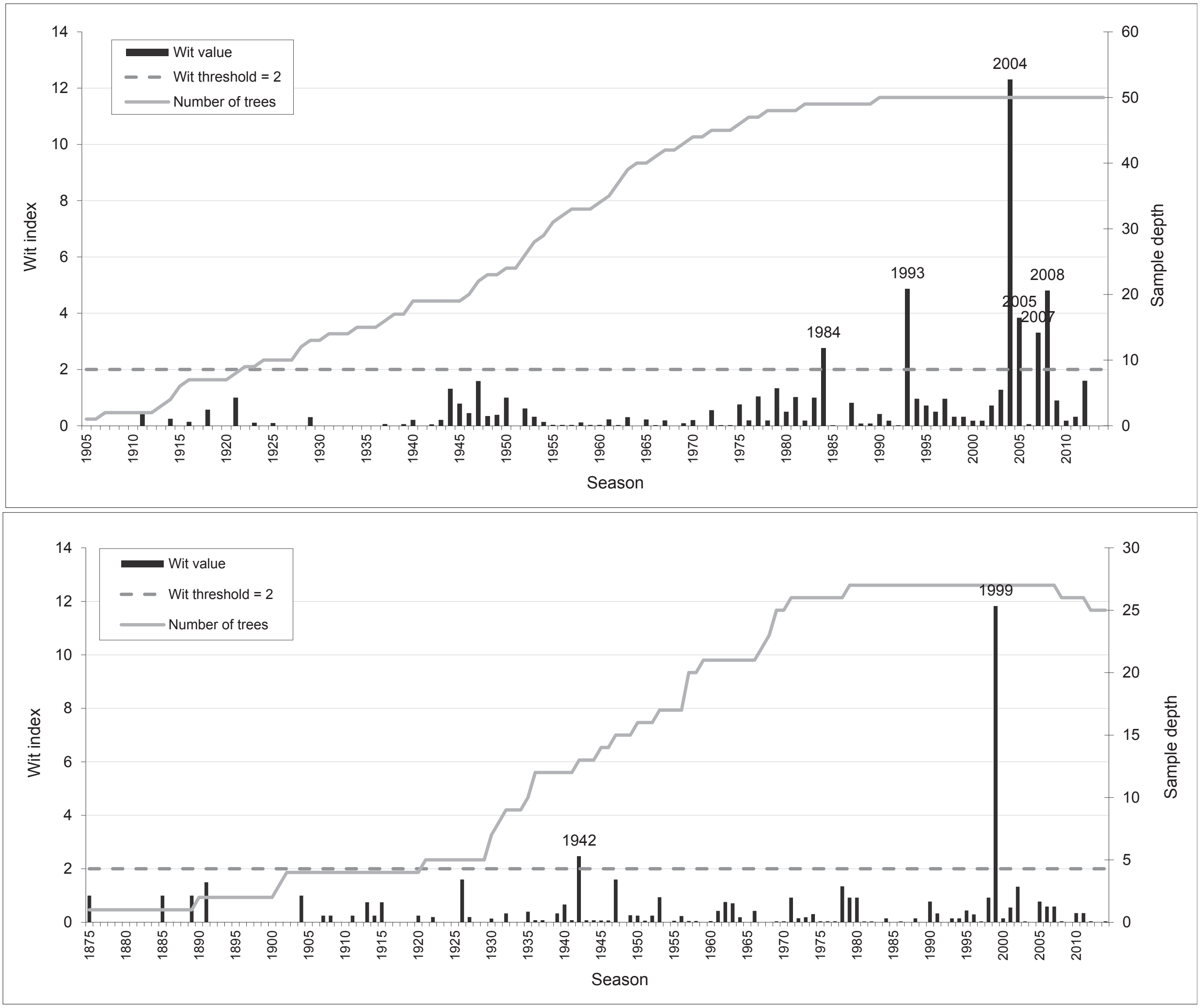

Fig. 3. Results of the dendrogeomorphic method.

5. Discussion

5.1. Avalanche activity and its relationships

The occurrence and frequency of avalanches in the Eastern High Sudetes is incomparably lower than in the western part of the High Sudetes (the Giant Mts.), where both the number of avalanche paths (98) and the average number of avalanche events per year (23) are greater (Kociánová et al., 2013). This is supported by the results of Tumajer and Treml (2015), who also revealed greater avalanche frequency in the Western High Sudetes. This difference is probably down to two causes: the smaller areas of summit plateaus above the alpine timberline (in the Eastern High Sudetes), which are the source of snow blown by the wind into leeward areas, and the position of the tree-line limit positioned ca 80 vertical metres higher, protecting slopes in the Eastern High Sudetes (Treml and Banaš, 2000). This supports the significance of alpine timberline altitude on avalanche formation, because higher position of forested area prevents avalanches in the mid-mountains. Dendrogeomorphic dating of avalanche events in alpine regions of the Rocky Mts., the Alps, the Tatra Mts. and the Fagaras Mts. (Butler et al., 2010; Corona et al., 2010; Chiroiu et al., 2015; Lempa et al., 2015; Pop et al., 2016; Schläppy et al., 2016; Voiculescu et al., 2016) shows higher avalanche frequency even in these areas. This is probably due to different meteorological conditions and higher relief energy, because the role of snow blown from planation surfaces is negligible in alpine mountains. The differing frequencies and different potential avalanche years between the two paths under study are probably down to differences in local factors, such as different slope gradient of starting zone and source area (see Fig. 2) and a smaller role of wind transportation of snow into the south-exposed Morava Hollow compared to other avalanche slopes located in more typical east- or south-east-exposed leeward hollows, because the prevailing wind direction in the mountains is from the west (Jancewicz, 2014; data from the meteorological stations on Mt. Praděd and Mt. Šerák).

Probable avalanche events with the greatest values of the *Wit* index, which affected the vegetation and probably the surface morphology, occurred in the avalanche years 2004 and 2008 in the Sněžná kotlina Hollow and 1999 in the Morava Hollow (Fig. 2). Our

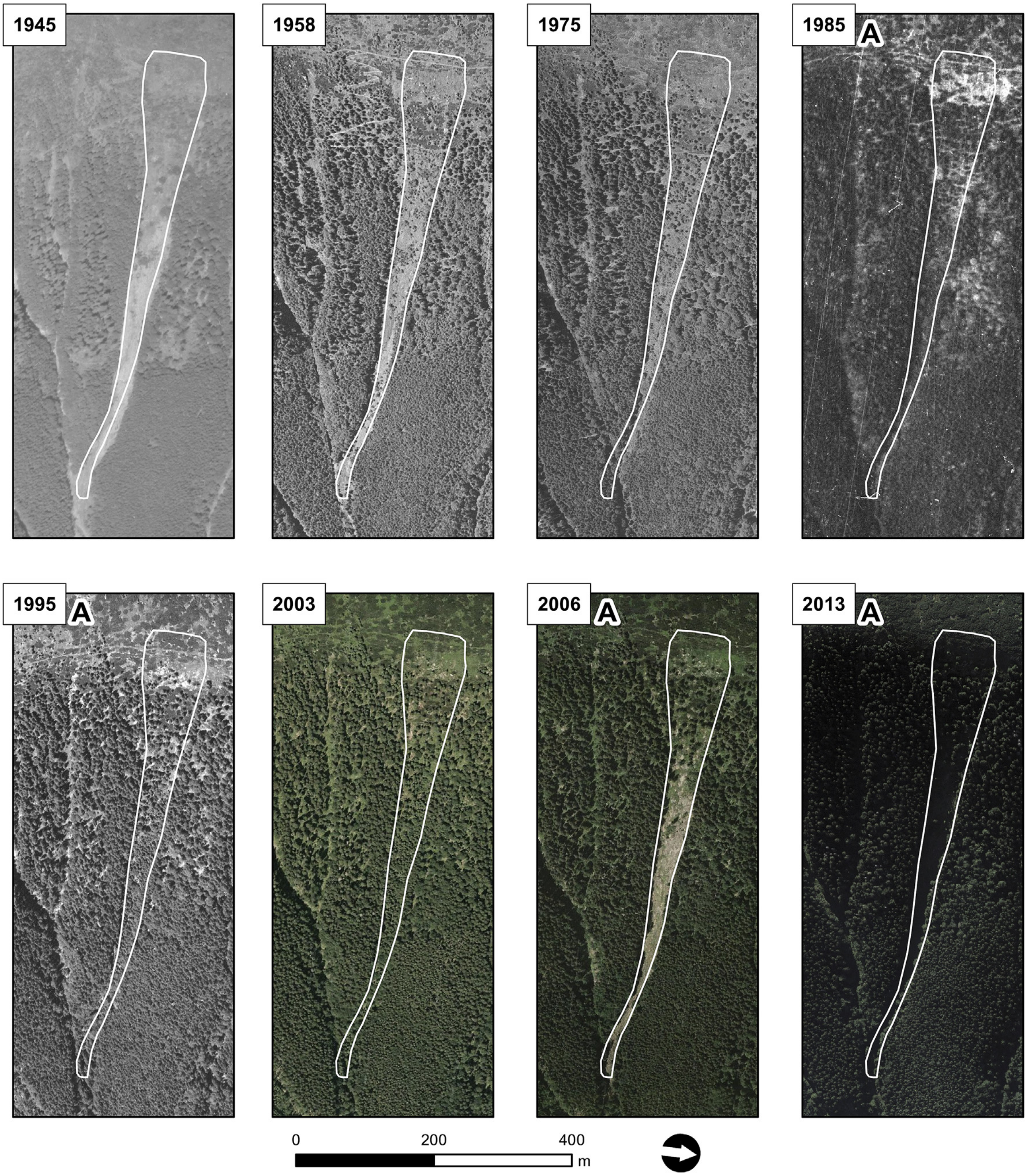

Fig. 4. Example of differences visible on the aerial photographs in the Sněžná kotlina Hollow. A—photograph taken after avalanche event dated with dendrogeomorphology.

comparison of dendrogeomorphic results and historical aerial photographs (Fig. 4) suggests that an avalanche event in 2004 severely damaged and completely removed trees growing in its path, strongly influencing the recent geomorphic development of the Sněžná kotlina Hollow. After this strong event, other avalanche events probably followed with greater frequency (years 2005, 2007, 2008) in the vegetation-free path. Avalanche events identified by the dendrogeomorphic method also reflect a relationship with avalanche events described in other paths of the mountains in the same seasons, as well as with extreme climatic features (Table 3), when 67% of avalanche records obtained by dendrochronology corresponded with climatic data and 83% of these data corresponded with avalanche activity. Rapid temperature increases to daily averages exceeding 10 °C and ensuing snow melt induced avalanche events in 2004, 2005 and 2007, and massive snowfall during March of 1993 probably caused a powder avalanche in the Sněžná kotlina Hollow, which have not removed the trees from the path (Fig. 4).

There is a possibility that the dendrogeomorphic method could not have detected all actual avalanche years (see Corona et al., 2012; Schläppy et al., 2013). Shorter powder avalanches could not have caused damage that could be detected by the dendrogeomorphic method. On the other hand, in the Western High Sudetes (the Giant Mts.), which are a similar mountain range, only 10% of all avalanches are represented by powder avalanches and about 30% of avalanches are represented by full-depth avalanches with the highest potential to affect vegetation (Kociánová et al., 2013). It is very likely that the same situation occurred in the Eastern High

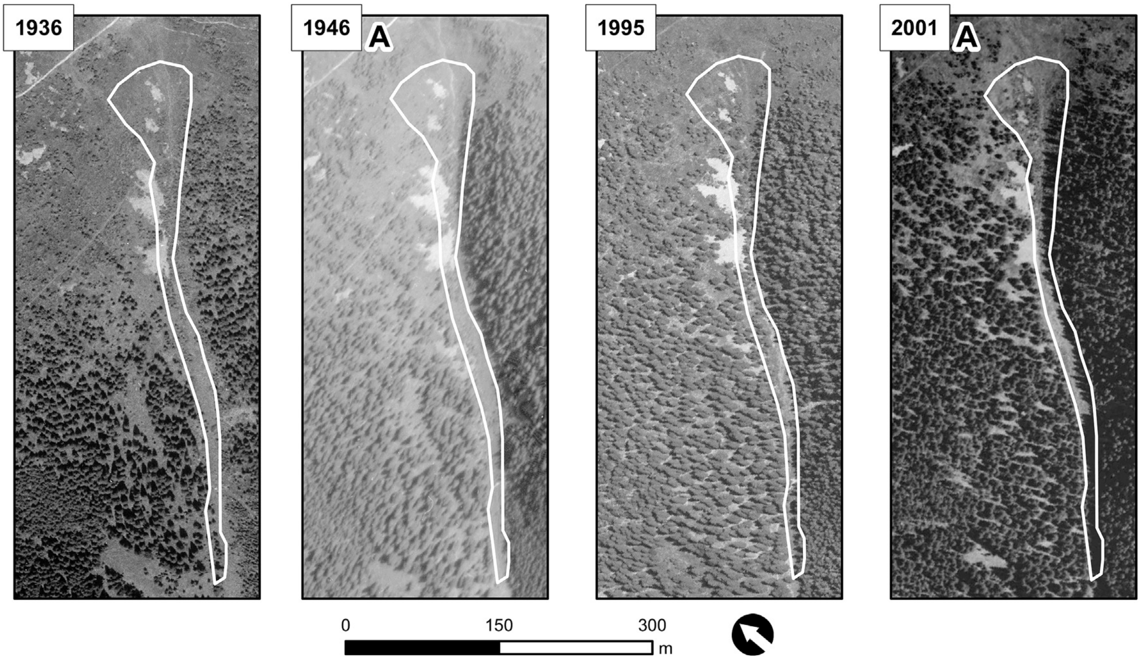

Fig. 5. Example of differences visible on the aerial photographs in the Morava Hollow. A—photograph taken after avalanche event dated with dendrogeomorphology.

Sudetes. Therefore, high values of the *Wit* index for some years might indicate avalanche activity in those years despite not exceeding the threshold; this is particularly plausible for the Sněžná kotlina Hollow path in the 1940s (1944 and 1948) and is also supported by missing vegetation in the path clearly visible on aerial photographs (Fig. 4). Unfortunately, the dendrogeomorphic method is unable to recognize the type of avalanche and its possible geomorphic impact.

The leeward position of the avalanche paths in upper sections of deep-sloped valleys in the Hrubý Jeseník Mts. and the Králický Sněžník Mts. corresponds with the situation in the Giant Mts. The Sněžná kotlina Hollow avalanche path has more significant values of geomorphic indices of avalanche activity, such as a gully (Fig. 2), similar to avalanche gullies described by Luckman (1977) and Rapp (1960). Another typical feature is the huge accumulation of logs in the lowest part of the avalanche path. Probable solifluction or debris-flow lobes also underline the ragged topography of the Sněžná kotlina Hollow avalanche path. On the other hand, the Morava Hollow path is much less ragged, and the role of avalanches in surface remodelling is negligible. The gully is present only in the central part of the path and it is very short and shallow. Other geomorphic avalanche forms are not present. Thus, the fact that the avalanche activity differs between these two tracks is well supported by their morphology. This is because avalanche landforms are visibly developed only in paths with greater avalanche activity.

5.2. Other slope processes in avalanche paths

Avalanche paths characterized by relatively long deforested slopes are typical of places suitable for the occurrence of other slope processes, typically debris flows (Stoffel et al., 2006). Debris flows are abundant also in the Eastern High Sudetes (Gába, 1992; Tichavský and Šilhán, 2015; Křížek, 2016). It is therefore highly probably that slope processes other than avalanches also played a role in the past. Remarkable lobes in the upper part of the Sněžná kotlina Hollow (see Fig. 2) look like they were not preconditioned by avalanches, but by solifluction or short debris flows. Štekl (2001), Hrádek and Lacina (2003), and Gába (2014) described huge debris flows on the western slope of Mt. Červená hora in June 1921. It is impossible to determine whether there was also a concurrent debris flow event in the avalanche path on the eastern slope of Mt. Červená hora. Štekl (2001) and Polách and Gába (1998) described extreme rainfall events and floods during recent history. This supports the possibility of debris flows in the avalanche path in the past. However, debris flow paths in the Eastern High Sudetes are usually located in different places than avalanche paths (see Gába, 1992; Roštínský et al., 2013; Tichavský and Šilhán, 2015), and paths shared by both phenomena have been described only in two sites: the Hučivá Desná Valley and the Sněžná kotlina Hollow (Sokol, 1965; Malik and Owczarek, 2009). In the Sněžná kotlina Hollow, Malik and Owczarek (2009) focused on slope movements (debris flows and avalanches) and their frequency based on the dendrogeomorphic approach. They believe that six debris flow events occurred in the path in the years 1968, 1971, 1972, 1977, 1991 and 1997. These debris flow events could not be supported by the results of this study. Moreover, the usual frequency of debris flow events in mid-mountains is markedly lower in the paths with more than one debris flow event (Pilous, 1973; Gába, 1992; Tichavský and Šilhán, 2015). The paper of Malik and Owczarek (2009) was based on a mere 19 living trees unequally distributed along the path. Moreover, they only used scars, abrupt growth changes and dead logs to determine potential avalanche years. The reference chronology used by the authors was constructed based on only 15 trees growing nearby on the slopes of Mt. Červená hora, and there is no conformity with the reference chronology used in this study or with other reference chronologies for surrounding areas (Ponocná et al., 2016). Furthermore, historical aerial photographs provide no evidence about potential debris flow events, such as changes in vegetation density caused by debris flow disturbance (Fig. 4). Debris flows also usually follow gullies (Pilous, 1973), and the occurrence of debris flows as wide as the entire avalanche path is highly unlikely (the distribution of damaged trees is loose), and not even marginal forms of debris flow tracks, such as levees, are visible on the terrain. This is why the existence of debris flow events described by Malik and Owczarek (2009) is highly improbable.

So far, there is no evidence of any slope processes other

Table 3
Verification of potential avalanche events and used sources.

	season	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
potential avalanche seasons	Sněžná kotlina Hollow				X											X	X		X	X							
	Morava Hollow										X																
avalanche seasons described in cited sources	Velká kotlina Hollow													X1					X3		X4			X6			X7
	Mezikotlí Hollow																					X5					
	Malá kotlina Hollow																X2										
*meteorologic situations suitable for avalanches**		X(t)			X(p)											X(t)	X(t)		X(t)			X(t)					

*p = snowfall with amount > 45 cm/day, t = day with average temperature over 10 °C during December, January, February and March.
*X1, X2–photographs by J. Chalpek from the year 2007; X3, X4–web pages of V. Kořízek alpy4000.cz from the year 2015; X5, X6–J. Chlapek (in verb.); X7–iDnes.cz on-line newspapers from the year 2015.

avalanches in the Morava Hollow avalanche path, but the terrain bears signs of creep movement (stems of trees). Together with fluvial activity and the rockiness of the hollow, it seems to be the main factor maintaining the unforested area below the upper tree limit. In contrast to other avalanche paths in the mountains, the role of avalanches appears to be minor in the case of this path.

6. Conclusions

Our dendrogeomorphic approach based on 271 samples taken from 96 trees revealed eight potential avalanche years in the Sněžná kotlina Hollow and the Morava Hollow in the Eastern High Sudetes. The results show clear differences in avalanche activity between these paths. Six potential avalanche years (1984, 1993, 2004, 2005, 2007, 2008) in the Sněžná kotlina Hollow and two (1942, 1999) in the Morava Hollow paths were investigated, though it is possible that some lesser avalanche events went undetected. The results of the dendrogeomorphic method were supported by a comparison with other avalanche and meteorological events in the mountains described in written sources and a comparison of historical aerial photographs. Most of the avalanche events investigated in the Sněžná kotlina Hollow corresponded with extraordinary meteorological situations such as days with average temperatures above 10 °C during February and March in the years 2004, 2005 and 2007, and heavy snowfall of over 45 cm of new snow per day in March 1993. This helped confirm the results that the probability of avalanche events is very high. A similar verification approach might prove useful also in other mountain ranges where information about avalanche activity is lacking.

The difference in avalanche frequency between the paths under study is remarkable, even though they are quite similar in their inclination, the topography of their surroundings and that they reach the closed forest. Especially after 2004, when very strong avalanche event, which erased all vegetation from its path, occurred in the Sněžná kotlina Hollow. The avalanche activity in the Eastern High Sudetes is lower, compared to the Western High Sudetes (i.e. the Giant Mts).

The geomorphic impact of snow avalanches is observable only in some paths in the mountain ranges. The typical avalanche gully in the Sněžná kotlina Hollow reflects frequent avalanche activity supported by results obtained by the dendrogeomorphic approach. On the other hand, there are no remarkable avalanche forms in the Morava Hollow, which means that avalanche activity is much lower there.

Other slope movements impacting the morphology of avalanche paths (debris flows) possibly occur in avalanche paths in the Eastern High Sudetes. For the avalanche paths studied here, however, there is no evidence of their recent occurrence. Debris flows in these mountains have recently occurred in places other than avalanche paths.

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