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ORIGIN, TRIGGERS AND SPATIO-TEMPORAL VARIABILITY OF DEBRIS FLOWS IN HIGH-GRADIENT CHANNELS (A CASE STUDY FROM THE CULMINATION PART OF THE MORAVSKOSLEZSKÉ BESKYDY MTS.; CZECH REPUBLIC)

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Abstract: High-gradient channels are integral parts of fluvial system in medium-high mountains and concentrate large amount of energy to origin of mass-wasting processes, such as debris flows. This study from the Moravskoslezské Beskydy Mts. tries to give a comprehensive view on debris flow initiation, spatio-temporal variability and potential triggers of these rapid channel processes. Main approach was dendrogeomorphic dating of affected trees supported by granulometric analysis of sedimentary fill and basin morphometric analysis. Geomorphological mapping revealed the most active zones of debris flow occurrence. Accurate tree-ring series dating of 55 samples (both deciduous and coniferous species) with growth disturbances showed 9 different debris flow events during the last 75 years with the highest peak in 1997. Meteorological conditions (extreme daily precipitation or spring melting of snow) allowed origin of debris flows despite the fact that recent sediment source areas occur sporadically. This leads to argument that reactivation of older deposits is the main process of recent debris flows origin. On the other hand, between 1950s and 1980s, when both basins were less covered by trees, there was possibility of higher slope and channel coupling and supplying sediments so debris flows should initiated even in less extreme meteorological conditions.

Keywords: debris flow, high-gradient channel, dendrogeomorphology, granulometric analysis, Moravskoslezské Beskydy Mts.

1. INTRODUCTION

Southern slopes of Lysá hora Mt. (central part of the Moravskoslezské Beskydy Mts.) are interwoven with the network of high-gradient channels. In general, they are defined as streams, where steep channel slope (minimum usually 1 to 5 %) affects channel morphology, sediment transport and flow velocity (Thompson et al., 2006; Rickenmann & Koschni, 2010; Galia & Hradecký, 2011). In the Czech Flysch Carpathians, high-gradient streams are still relatively overlooked parts of fluvial system; on the other hand they represent places with frequent occurrence of fast geomorphological processes, such as debris flows (Šilhán, 2012). Debris flows (DFs) are dangerous geomorphic process characterized as a movement of solid material and water, when incoming sediments have a control function of movement and they are also prevailing element of this substance (Pierson, 2005). Jakob & Hungr (2005) define debris flow as a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel. Sediments and water form a single unit so they move together as a plastic (Baker et al., 1988) and new accumulation (lobes, terraces) and erosional (bedrock forms, bank or slope failure) landforms are the consequences of this movement (Jakob & Hungr, 2005; Brayshaw & Hassan, 2009). That is why landforms created by debris flows are mostly well mapped.

Debris flows represent relatively complicated problem in terms of research. It is necessary to emphasize, that it is not a single process occurring in high-gradient channels so in most cases of mountainous regions, the construction of fans is combined also with fluvial processes (Scally & Owens, 2004; Šilhán, 2014). The key to reveal the initiation of accumulation and erosional landforms in channels and understanding of stream functioning under certain climatic conditions is connected with many methods of research. Studies focus on basin morphometry (e.g. Bovis & Jakob 1999; Scally & Owens, 2004), lithological and tectonic conditions (e.g. Malet et al., 2005, Sterling & Slaymaker, 2007), sedimentological characteristics (e.g. Scally & Owens, 2005) and currently dendrogeomorphic methods – tree ring analysis (e.g. Stoffel et al., 2008; Zielonka et al., 2008; Šilhán, 2012). Trees affected by debris flows represent valuable natural archive, because they can record the event in their tree ring series (Bollschweiler & Stoffel, 2010), so we can analyze how frequently and when did events occur, how far did they reach or what was the magnitude of event (Stoffel & Bollschweiler, 2009). Dendrogeomorphic methods are actually the best approach to date debris flows in far-flung catchments which are covered by trees.

The main aims of this study are (1) to explain initiation and genesis of debris flows in two high-gradient channels on southern slopes of Lysá hora Mt. (the Moravskoslezské Beskydy Mts.), (2) create spatio-temporal reconstruction of debris flow activity using dendrogeomorphic methods, (3) to evaluate character and mechanism of the process.

2. STUDY AREA

Research of debris flows was focused on two high-gradient channels (the Jatný and the Řehucí) in the culmination part of the Moravskoslezské Beskydy Mts. which are the part of Western Carphatians (Fig. 1). Both basins of high-gradient channels are situated on southern slopes of Lysá hora Mt. (1323 m a.s.l.) – the highest peak of the mountains. Recent thrust-and-fold structure of this mountain range is closely connected with tertiary folding when flysch-type sediments were transported by orogenic movements onto a marginal part of the Czech Massif (Menčík et al., 1983).

Periglacial processes participated on development of mountains in Pleistocene; currently fluvial processes dominate (Buzek et al., 1986).

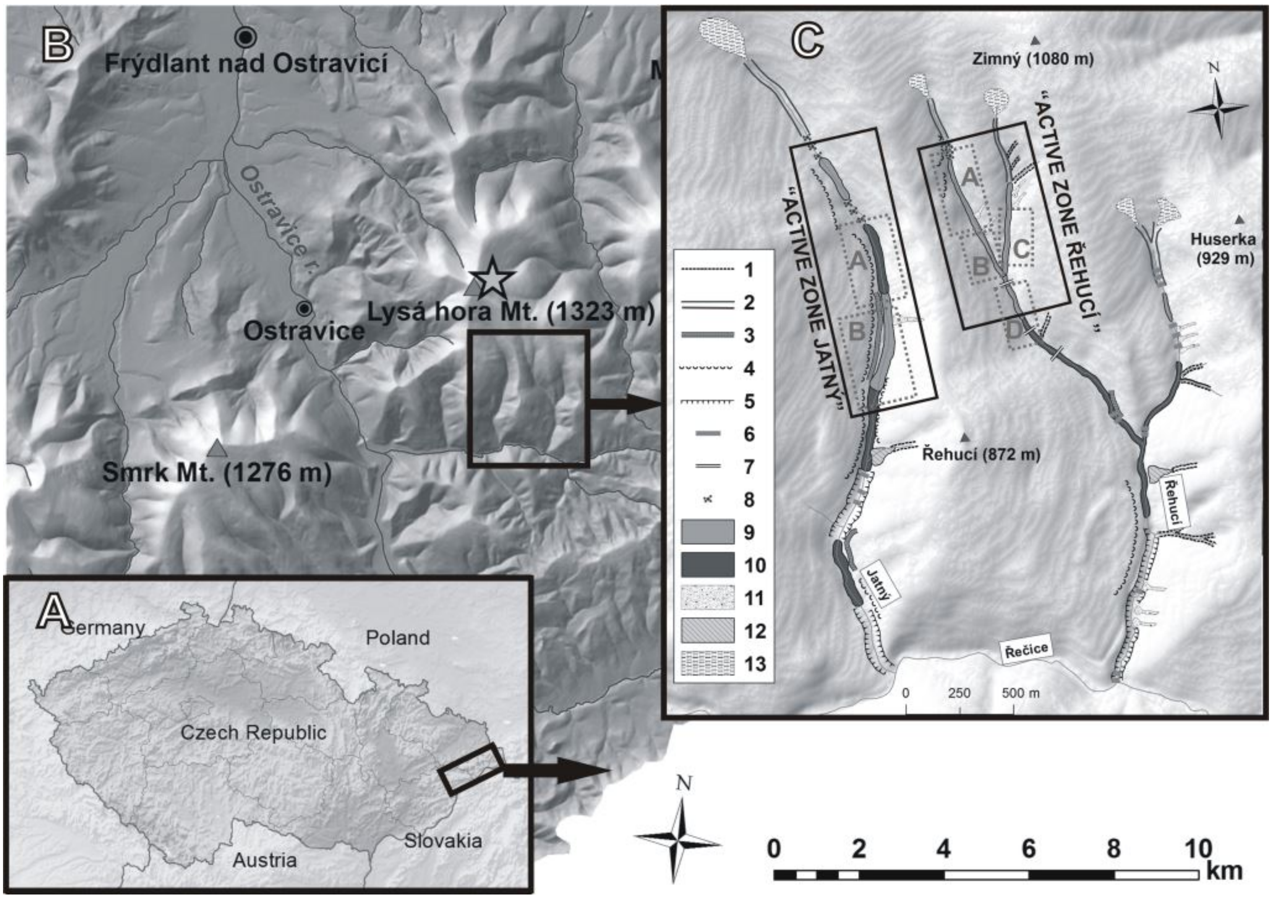

Figure 1. A – Position of the Moravskoslezské Beskydy Mts. in the Czech Republic, B – Position of the study area in the Moravskoslezské Beskydy Mts. (meteorological station on Lysá hora Mt. is marked with a star), C – Detailed view of both high-gradient channels (1 – gully, 2 – transport zone of DFs, 3 – terrace of fossil DFs, 4 – unstable slope, 5 – channel incised to bedrock, 6 – channel bed step, 7 – anthropogenic dam, 8 – boulders, 9 – DF accumulation zone, 10 – stable fluvial accumulation zone, 11 – colluvial fan, 12 – fossil alluvial fan, 13 – source zone of DFs; zones of sedimentary fill sampling is marked by grey dotted line).

Typical features are also deep-seated landslides affecting flysch bedrock (Hradecký & Pánek, 2008, Pánek et al., 2009). Southern slopes of Lysá hora Mt. are formed by sandstone benches interlaced by thin layers of claystones or siltstones, usually covered by quaternary deposits of Pleistocene weathering. Whereas the Řehucí is formed by fine to moderate rhythmic flysch with prevailing siltstones and fine grained sandstones interlaced by claystones, lithological conditions in the Jatný are slightly different: thick benches of sandstones (1 – 2 m) are accompanied by several cm thick layers of clayey shale. Both studied basins are well morphometric exposed to origin of fast slope processes (mean slope is higher than 20°; locally even 40°; Table 1). The Jatný as well as the Řehucí spring in the altitude of 1 000 m a.s.l. and after 3 km flow into the Řečice (the right tributary of the Ostravice). This part of the Moravskoslezské Beskydy Mts. belongs to the rainiest areas in the Czech Republic with annual precipitation exceeding 1 400 mm (Kříž, 2004, Tolasz, 2007). Basins are almost fully covered by forest (mostly represented by European beech (*Fagus sylvatica L.*) and introduced Norway spruce (*Picea abies (L.) Karst*.), in lower parties also sycamore maples (*Acer pseudopatanus L.*)). The involvement of forest changed throughout the centuries and also in the 20th century due to cutting of trees followed by introductions of unoriginal spruces, then due to damage by air pollution (Buzek et al., 1986). Deforestation can affect dynamics of slopes which leads to sediment weathering and potentially new source zones of debris flows can origin (Koscielny et al., 2009).

Fast channel processes and water flow erosion in the Moravskoslezské Beskydy Mts. was first studied in detail by Buzek (1982). Research of debris flows is sophisticated and studies try to give a comprehensive view of this problematic in recent few years (see Šilhán & Pánek 2010; Šilhán, 2014).

3. METHODOLOGY

The methods used for analyzing these two high-gradient channels should (1) confirm occurrence of debris flows (demonstrating fossil and recent accumulations), (2) find out their frequency, spatial reach and triggers. Based on these approaches try to describe the initiation and genesis during the last decades.

3.1. Geomorphological mapping and analysis of basin morphometric parameters

Detailed geomorphic mapping of valley bottom and adjacent slopes in a large scale (1:10000 and 1: 1000) was carried out in July 2012 to bring information of actual condition of source, transport and deposition areas of both streams and to identify fossil and recent debris flow accumulations. Observed data were transferred to ArcGIS software and used for creation maps. Using digital elevation model (resolution 15 m) basin morphometric parameters were calculated with aim to verify potential predisposition of valley to debris flow origin. Special attention was paid to Melton index (R) – an index expressing basin dynamics and predisposition to initiation of debris flows (Melton, 1965). Index was calculated according:

$$R = h_b.A_b^{-0.5}, (1)$$

where h_b is the basin relief and A_b is the basin area. The values of Melton index exceed 0.25 which is the threshold for potential occurrence of debris flows (Dikau et al., 1996; Wilford et al., 2004).

3.2 Dendrogeomorphic dating of DF accumulations

During the terrain reconnaissance, increment cores from trees, which displayed the signs of disturbance (injuries, tilting or stem burial), were extracted using Pressler increment borer (max. length 40 cm; diameter 0.5 cm). GPS position of all sampled trees was recorded in the geomorphic map (Fig. 5). Also sampling of two-cm-wide cross sections from exposed and affected roots was useful to finding a year of debris flow event. Together 48 samples (increment cores and cross sections; 33 from the Řehucí and 15 from the Jatný) – both from coniferous species (*P. abies*) and deciduous species (*F. sylvatica, A. pseudoplatanus*) – were analyzed using standard methodology described by Shroder (1978) or Stoffel & Bollschweiler (2008). The cores were dried, glued into woody supports, smoothed and polished, so they were prepared to tree-ring counting. Tree-ring widths were measured using TimeTable (accuracy 0.01 mm) and software PAST4 (Vienna Institute of Archaeological science, 2005).
Individual events were dated on the principles of concept "process – event – response" (Shroder, 1978) where certain geomorphological processes (e.g. debris flows) influence tree growth (e.g. wounding, stem tilting or burial) and left specific growth response in tree-ring series of affected trees (Fig. 2).
Growth disturbances (GD) can be different: abrupt growth suppression (as a result of stem burial caused by moving material or in case of stressful situations induced for example by undercutting the bank, where tree grows), abrupt growth release (in reaction to the death of adjacent trees followed by lower competition

of survivor trees), formation of callus tissue (as a result of stem/root wounding), traumatic resin ducts (TRD; response to the stem wounding of some coniferous species) or formation of reaction wood (when tree is leaning from normal position, due to mechanical pressure of debris flow material, forms asymmetric compensation rings on one side of the stem: compression wood in coniferous species on the lower side, tension wood in deciduous species on the upper side of the stem) (Bollschweiler & Stoffel, 2010). To eliminate noises in tree-ring series (false or missing rings) and to distinguish between geomorphic and non-geomorphic origin of growth disturbance, the reference increment curve of 30 undisturbed trees from Lysá hora Mt. region was used. Due to relatively small amount of samples, the semi-quantitative approach (Bollschweiller et al., 2007) of determining the debris flow events based on spatial distribution of trees was used (three samples with logical spatial position showing geomorphic event in the same year).

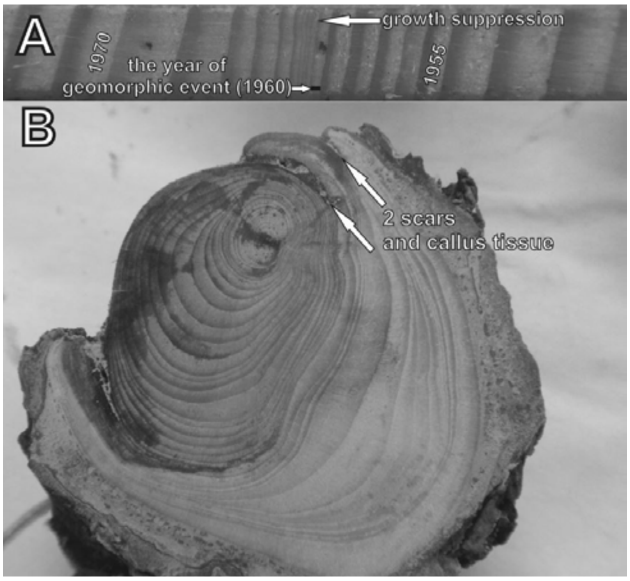

Figure 2. A – Growth disturbance in the form of growth suppression on the increment core of *P. abies*. B – Growth disturbance in the formation of callus tissue on the cross section of *P. abies*.

3.3 Meteorological conditions in the study area

Evaluation of meteorological data was carried out to evaluate potential triggers of debris flows. According to Iverson (1997) and Bollschweiler & Stoffel (2010) it is necessary to concentrate on extreme precipitation (convective high-magnitude short duration precipitation or extreme rainfall lasting few days) and rapid snow cover melting in spring. These factors were the most important in analyzing debris flow triggers. Data were collected from meteorological station at Lysá hora Mt. (1323m a.s.l.) which is the nearest and the most suitable object for studied basins (Fig. 1B). Valuable meteorological series dates back to 1897 and apart from few outages it is continuous. Data were analyzed and the most extreme rainfalls were compared with dendrogeomorphic results. According to Zielonka et al., (2008) the snow-melting factor was calculated as difference among mean April and May temperatures. The attention was also paid for maximal snow cover height in these months.

3.4. Sedimentological analysis of debris

Sediments from active accumulations are valuable especially to understand the functioning of material movement and weathering. To confirm and precise the genesis of accumulation forms in both valleys, representative samples (weight from 300 to 500g, maximal size of particles two cm) of fine sedimentary fill (matrix) were extracted from active lobes for grain-size analysis. Then the samples were dried and subsequently the wet sieving procedure of separation grain-size fractions using set of sieves was performed. The weights of each fraction were transferred to GRADISTAT software (Blott & Pye, 2001) and basic grain-size parameters (mean grain size, sorting) were derived. The mud – sand – gravel diagram was used for analysis of the finest material (matrix).

4. RESULTS

4.1 Geomorphology and morphometric situation of studied valleys

Both valleys are clenched by steep slopes, especially from the east side. In the lower parts, the streams incise to the bedrock and small channel bed steps are formed due to higher slope gradient. Middle parts of both valleys represent the riffle – pool system with lateral or central bars. Above the elevation of 650 – 700 m a.s.l. channel gradient starts increasing and it is obvious, that the dynamics of valley is higher (frequent occurrence of bank failures and fresh accumulations). Difference between both valleys in the “active zone” (zone with the most fresh morphology of forms) is evident from the figure 3. In the Řehucí, the active zone with debris flow accumulations is uninterrupted (Fig. 3A, 3C); in the Jatný (Fig. 3B, 3D), we can observe more changes in values of slope gradient and the consequences are zones of active and stable accumulation forms (lateral levees, frontal lobes). From the surrounding slopes several small colluvial fans mouth into channels and supply sediments to the streams (Fig. 6F). Depositional forms of debris flows are morphologically the most evident. There are lobes (DFL, Fig. 6E) up to tens of meters long and two meters wide (with heterogeneous material from matrix to boulders), lateral boulder levees along the channel margins and isolated boulders up to three meters long. Apart from active forms (Fig. 4A) there are also evidences of fossil debris flow accumulations in the form of several meters high terraces above the channel bed, which are the remnants of large accumulations previously filling the original bottom (Fig. 4B). Channel sedimentary fill is accompanied by woody material, which forms log jams in some parts of channel. There are no signs of fresh source zones of debris flows on slopes. Instead, character of material sources have occasionally occurred bank-failure-type erosional forms direct on surface of older debris flow accumulations.

Morphometric analysis describes the basic facts of both basins. Mean slope exceed 20° in both basins and therefore they are the most exposed in the Moravskoslezské Beskydy Mts. Difference between maximum and minimum value (basin relief) of altitude is 653 m in the Řehucí and 800 m in the Jatný. Drainage density is bigger in the Řehucí (1.65 km / km^2) than in the Jatný (1.01 km / km^2) because of slightly different lithological conditions. The values of Melton index (0.34 in the Řehucí and 0.43 in the Jatný) exceed the threshold for occurrence of debris flows. Other morphometric parameters are recorded in table 1.

Table 1. Morphometric parameters of both basins.

	Řehucí	Jatný
Minimal altitude (m a. s. l.)	553	523
Maximal altitude (m a. s. l.)	1206	1323
Stream length (km)	3.1	3.11
Thalweg length (km)	3.95	4.14
Basin area (km^2)	3.64	3.49
Drainage density (km/km^2)	1.65	1.10
Basin relief (m)	653	800
Mean slope (°)	20.3	22.8
Melton index	0.34	0.43

4.2 Dendrogeomorphic data

The age of tree (sample depth – SD) allowed dating since the beginning of the 20th century, but most of the trees are in the maximum of 50 years old (Fig. 5A). Together 55 growth disturbances from the Řehucí and 48 growth disturbances from the Jatný were identified and dated (Table 2).

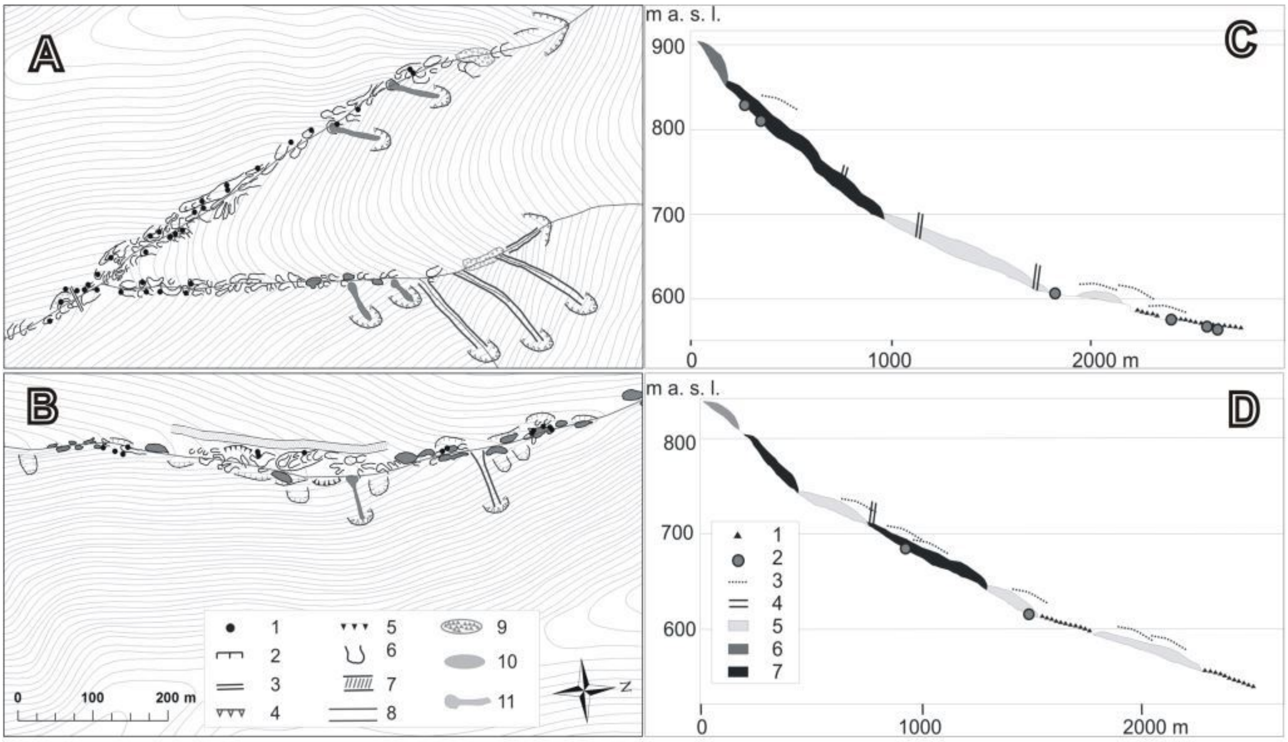

Figure 3. Detailed geomorphic maps of the active zones: A – the Řehucí and B – the Jatný (1 – position of sampling trees, 2 – bank or slope failure, 3 – anthropogenic dam, 4 – sediment source area, 5 – bedrock, 6 – DF lobes, 7 – terrace of fossil DFs, 8 – gully, 9 – boulders, 10 – stable fluvial accumulation, 11 – colluvial fan). Difference between positions of DF accumulations within the longitudinal profiles: C – the Řehucí and D – the Jatný (1 – channel incised to bedrock, 2 – mouth of colluvial or alluvial fan, 3 – unstable slope or slope failure, 4 – mouth of gully or stream branch, 5 – stable fluvial accumulation zone, 6 – boulders zone, 7 – zone of DF accumulations).

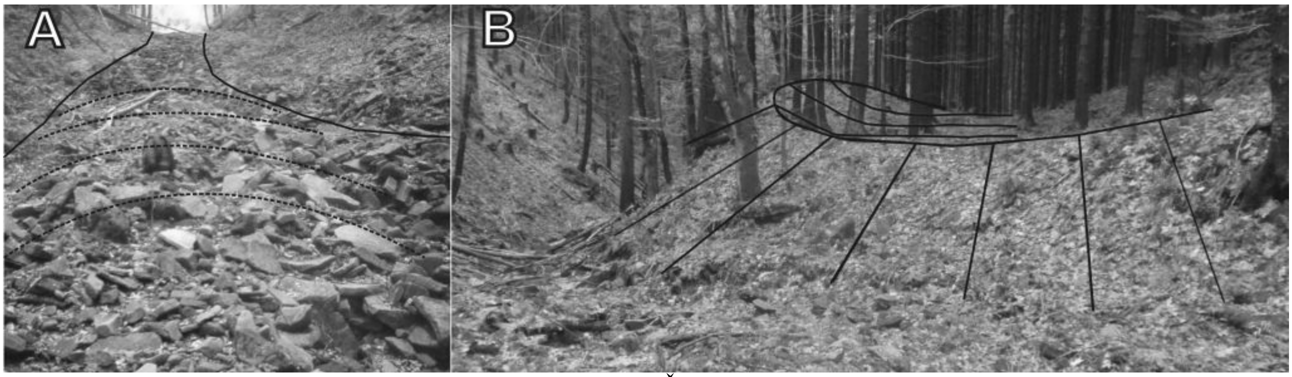

Figure 4. A – Recent fresh DF lobes in the active zone of the Řehucí, B – Fossil DF accumulation in the form of terrace in the Jatný.

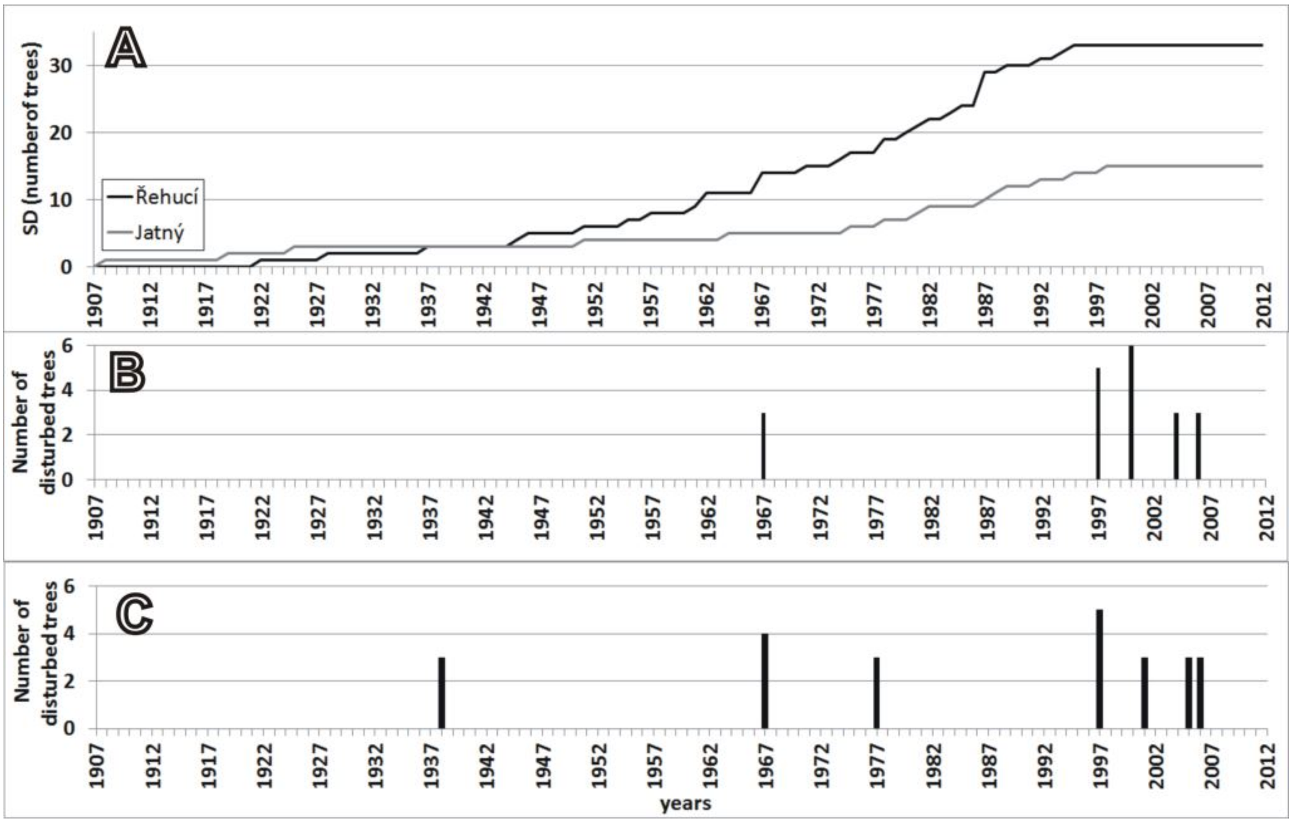

Figure 5. A – Sample depth of trees in both valleys. B – Identified debris flow events in the Jatný. C – Identified debris flow events in the Řehucí.

Table 2. Number and percentage of growth disturbances in sampled trees.

Type of growth disturbance	Jatný		Řehucí	
	Number	%	Number	%
Growth suppression	10	20.8	23	41.8
Growth release	8	16.7	10	18.2
Traumatic resin ducts	3	6.2	1	1.8
Reaction wood	14	29.2	9	16.4
Callus tissue	13	27.1	12	21.8
total	48	100	55	100

In the first-mentioned area abrupt growth suppression in tree-ring series dominates, in the second there are mostly reaction wood and callus tissue. The oldest reaction is dated to the year 1903 (callus after scar) in the Řehucí. There is also evident that the formation of reaction wood occurs mostly in the last 15 years (earlier only in one case). On the contrary in the Jatný the occurrence of reaction wood is bounded even with the 1st half of the 20th century. The most frequent years of any growth disturbances are the 1997 and 1967 in the Řehucí and 2000 and 1997 in the Jatný. The oldest confirmed event of debris flow (with three growth disturbances) is the year 1938 in the Řehucí. Although it was found out many years with growth disturbances, most of these, in which three and more responses were recorded, are the years typical for both valleys (e.g. 1967, 1997 or 2006) (Fig. 5B, 5C).

Many growth disturbances were identified in the last 10 years. On the other hand, the years with less than 3 GD can't be considered as a year of debris flow origin.

4.3 Spatio-temporal patterns of debris flows and possible triggers

Dendrogeomorphic research provided information about older and also more recent debris flow events. Using the accurate position of affected trees and their spatial relationship to debris flow accumulations it is possible to reconstruct spread and frequency of these events. In the Řehucí (Fig. 5C), seven debris flows were determined (1938, 1967, 1977, 1997, 2001, 2005 and 2006). In 1938 there is no spatial relationship between position of affected trees as well as in 1967 (Fig. 6A, 6B). The year 1977 is represented by three growth responses and occurs only in the right branch of the stream (Fig. 6C). In the upper part there is evidence of activation of ~ 100 m long part of accumulations, where two trees were affected. Probably the strongest flows initiated in 1997 (five growth disturbances in four trees were identified and two occurrences of reaction wood dated to 1998 were attributed to the event of 1997 according to spatial relationship between the trees), when lower part of debris flow accumulations was activated (Fig. 6D). Length of this part is from 200 to 300 m and it seems that the movement was stopped at the place of old anthropogenic dam. Below the dam there is no record of growth disturbance in 1997.

Potentially in 2001 debris flows could occur, but only two trees with three responses were identified. Reconstruction of recent movements clearly shows that debris flows initiate also in the last several years and the position of affected trees is localized mostly in the lower part of active zone.

In the Jatný (Fig. 5B), five debris flow events were identified (1967, 1997, 2000, 2004 and 2006). Due to different geomorphic situation, the spatial distribution of debris flow accumulations is not as obvious as in the Řehucí, nevertheless valuable results are from the years 1997 and 2000. Five growth disturbances from three trees belong to 1997 and the position is at the beginning, in the middle and also at the end of the active zone indicating that the movement took place in the whole active area just as in the 2000 (six trees were affected). In this year, we can definitely confirm the movement in the lower part because of spatial distribution of the trees. Reconstruction of recent activity shows (as in the previous valley) occurrence of debris flows also in the whole "active zone" (Fig. 7A). The farthest place of sampling reports interesting fact in activity of channel processes. Having regard to the channel morphology with extensively eroded banks of river isle and occurrence of active lobes (Fig. 7C) there was an assumption of recording the events in the trees on isle. In the five trees 17 growth disturbances in 16 different years from 1925 to 2010 were analyzed so it shows to high frequency of events and activity or reactivity of channel accumulations is ongoing continuously (Fig. 7B).

Dendrogeomorphic results were compared with meteorological data from Lysá hora Mt. (1323 m a. s. l.). Most of identified debris flows are connected with extreme daily precipitation exceeding 60 mm / day, with maximum in July 1997 of 233.8 mm (Tab. 3). Only 2004 and 1967 are probably connected with another trigger. If we use the melting snow factor for the year 1967, there is evidence that 110 cm per eight days melted at Lysá hora so spring floods could affected both valleys. Overall, the years with most growth responses (1997 the Řehucí, 2000 the Jatný) are also the years with the highest precipitation of all these identified DF events.

4.4 Sedimentological parameters of DF accumulations

Together 28 samples were extracted from accumulations of "active zones" (21 from the Řehucí and 7 from the Jatný). The mud – sand – gravel diagram (Fig. 8A) shows that the most of samples from the Řehucí are classified to Muddy Sandy Gravel category, nearby Sandy Gravel and Gravel. Similarly in the Jatný most samples are classified to the same category. More than one grain size fraction is represented in each sample and none of these dominates. Sand fraction is represented by almost the same percentage (about 35 %) in both valleys, slight difference is between the percentage of mud and gravel fraction (Table 4).

Table 4. Basic sedimentological parameters of DF accumulations (sedimentary fill) in studied valleys.

		Řehucí	Jatný
Samples		21	7
Mean grain size (µm)	Mean	1576.2	1469.4
	Minimal	228.6	686.9
	Maximal	3093.4	2478.6
Sorting (µm)	Mean	4.36	5.98
	Minimal	1.74	2.68
	Maximal	11.12	11.22
Mean grain fraction proportion (%)	Gravel	62.2	54.8
	Sand	35.3	34.9
	Mud	2.5	10.3

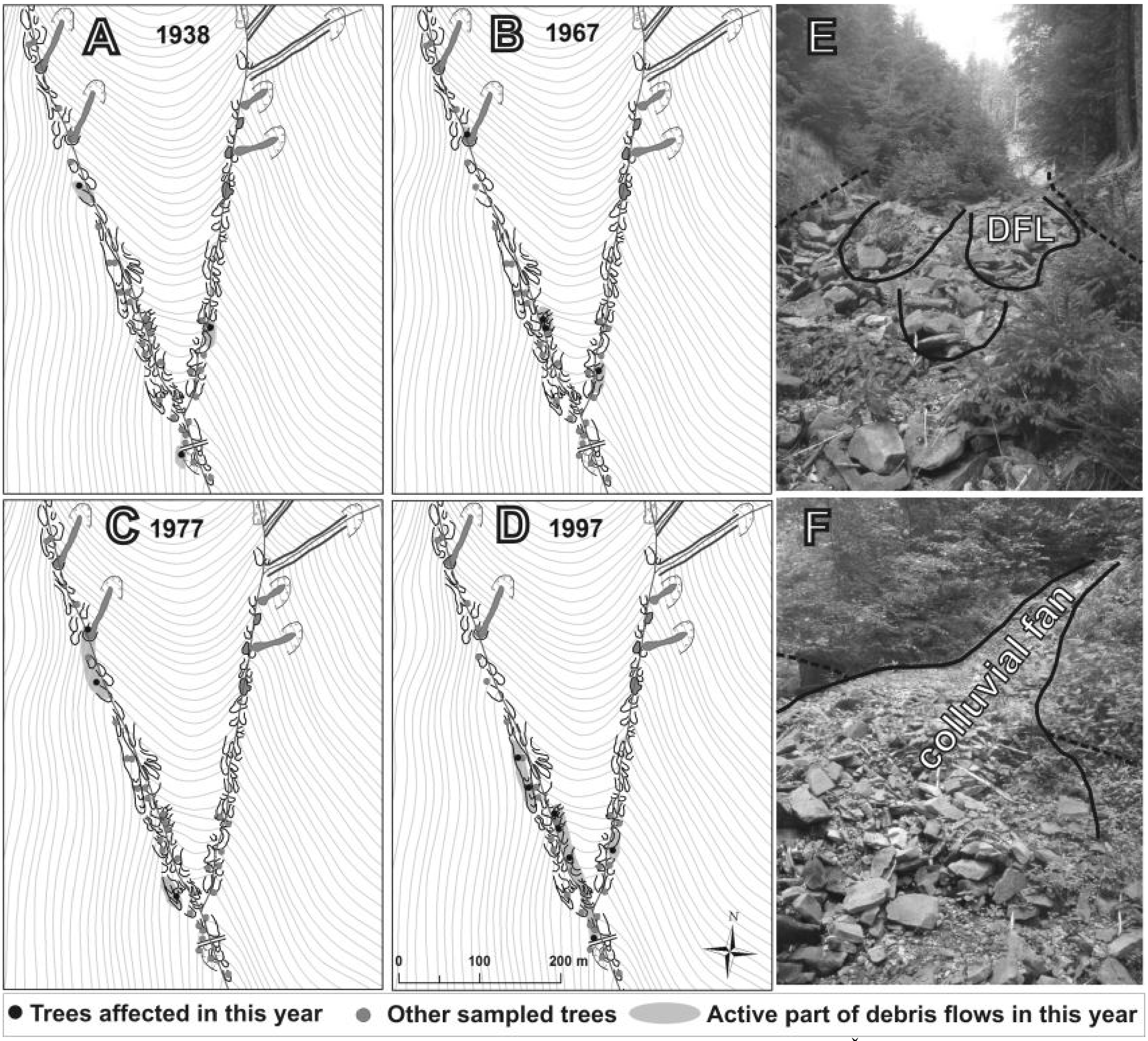

Figure 6. Spatio-temporal reconstruction of debris flow activity in selected years in the Řehucí with photos of current (2012) conditions of DF accumulations and small colluvial fans.

Other parameters under research are mean grain size and sorting coefficient. Mean grain size in both valleys exceeds 1400μm indicating very coarse sand whereas the range of values is higher in the Řehucí basin. Results of sorting coefficient indicate the total unsorting of samples. Material is very poorly sorted whereas the range is almost the same.

For better understanding of sedimentological parameters, areas of active accumulations were divided into several zones depending on their morphological parameters and then the results (sorting, mean grain size and percentage of individual fractions) from granulometric analysis were compared. In the Řehucí, there is zone A (upper part of the active area, accumulations are in places overgrown by vegetation or young trees), zone B (lower part of the active area which seems to be the most active), zone C (left branch of the stream with not so many accumulations) and zone D (below the confluence of both branches) (Fig. 1C). No crucial relationship between upper and lower part was determined. The minimum value of sorting coefficient is in the upper part, where is also the maximum of mean grain size. In the percentage of grain fraction, we can see decrease of gravel fraction in the direction of flow (Fig. 8B).

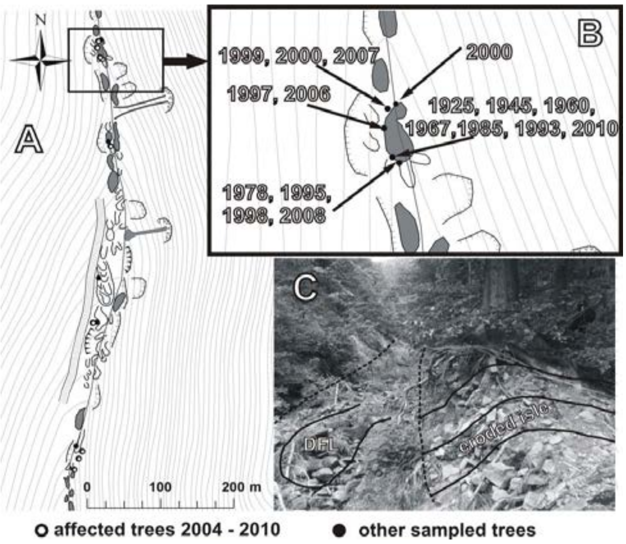

Figure 7. Spatio-temporal reconstruction of recent debris flow activity in the Jatný with situation at the farthest place of sampling (Figure 7B and 7C).

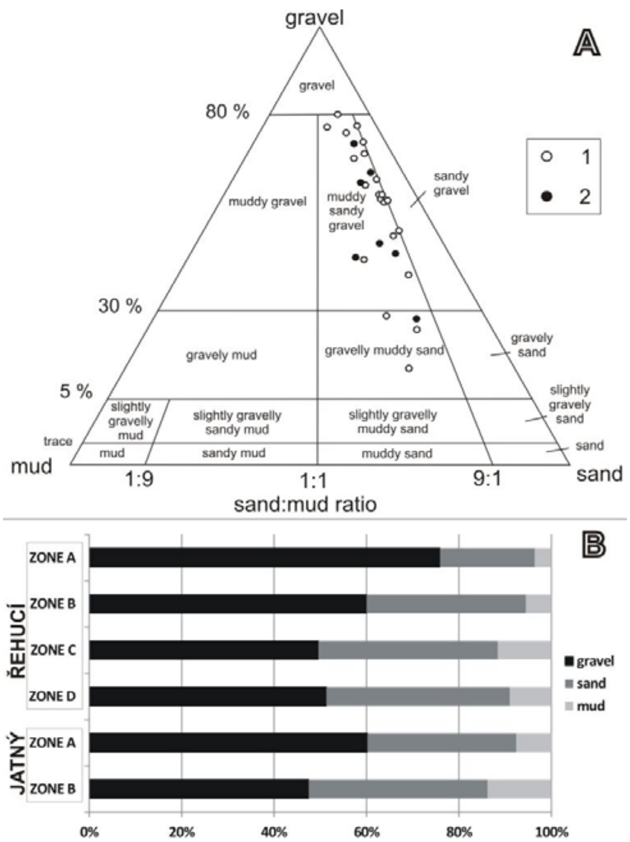

Figure 8. Graphic results from granulometric analysis from sedimentary fill of DF accumulations. A – The mud – sand – gravel diagram for the Řehucí (1) and the Jatný (2). B – Percentage of different grain size fraction in active zones according figure 1C.

5. DISSCUSIONS

Detection of fossil and recent debris flow accumulations is also confirmation that climatic conditions allowed the origin of fast channel processes such as debris flows in studied area. Šilhán & Pánek (2010) mention occurrence of these both types of debris flow deposits in several parts of the Moravskoslezské Beskydy Mts. and it is obvious that apart from significantly larger fossil accumulations, the recent conditions enable the initiation of similar channel processes, but probably in smaller scale. A key method of this research was dendrogeomorphic dating of debris flows.

Both coniferous and deciduous trees were dated, which was not routine in European dendrogeomorphological studies. Mayer et al., (2010), Stoffel et al., (2010) in Alps, Zielonka et al., (2008) in Tatra Mountains or Bodoque et al., (2005) in central Spain identified the events on the basis of samples of coniferous species (also depended on vegetation cover). Using of broadleaved species in medium-high mountains is mentioned by Šilhán (2012) and is examined in detail by Arbellay et al., (2010). Currently it is called for the use of both types of trees (deciduous and coniferous), if it is possible, and for balanced sampling of older and younger trees (Stoffel et al., 2013). This study brings almost equilibrium in both types of trees and the age structure is also varied.

Together seven debris flow events in the Řehucí and five debris flow events in the Jatný were identified. It is obvious that several events in the same years occurred in both valleys (1967, 1997, and 2006) which should make sure about their initiation. Regional flood in July 1997 is characterized as the biggest natural disaster of the 20th century in the Central Europe. Daily precipitation on the July 6th reached 234 mm and during four days it rained 586 mm at Lysá hora Mt. (Brosch, 2005). Extreme precipitation exceeded 60 mm occurred in the same year several times. In 1967 it is possible, that intensive spring melting of snow should cause the movement of material in channel (Table 3). In the middle of April and repeatedly at the end, the amount of more than 100 cm of snow melted at Lysá hora Mt. and daily temperature fluctuated about 6°C. Melting of snow accompanied by high temperature and precipitation may lead to the floods, but also many other factors enter to storage and melting of snow such as altitude, slope gradient, slope exposition and vegetation cover. Due to deforestation of both basins in the second half of the 20th century, initiation of debris flows by snow melting was possible. We must be careful in assessment of more frequent recent activity than for example in the 1st half of the 20th century. It is probable that significant part of older forest was damaged by deforestation or air pollution so we should not overestimate the results from last 20 years and underestimate earlier processes (Šilhán, 2014).

Table 3. Meteorological data from years of DF events. Extreme daily precipitation or extreme melting of snow could be the trigger of DFs.

	Precipitation		Number of days (24h precipitation)			Melting snow factor	
Year	Mean annual (mm)	Maximum 24h (mm)	> 100 mm	80 - 100 mm	60 - 80 mm	Snow melting	Temperature difference (°C)[2]
2006	1392	88,3	0	1	0	No fluctuations[1]	3,6
2005	1581,3	61,5	0	0	2	No fluctuations	4,5
2004	1291,2	40,3	0	0	0	No fluctuations	2,3
2001	1907,7	80,1	0	1	3	No fluctuations	7,4
2000	1627,6	135,3	2	0	2	105 cm per 8 days	4,5
1997	2063,6	233,8	4	0	2	100 cm per 9 days	9,8
1977	1829,7	111,3	1	1	2	80 cm per 7 days	6,6
1967	1254,3	53,3	0	0	0	110 cm per 8 days	6,8
1938	1709,3	93,2	0	2	2	No fluctuations	7,4

1 - snow melting less than 60 cm per seven days; 2 - difference between mean temperature of April and May

For instance, several growth disturbances were identified between 1900 and 1930 and most of them may be connected with extreme meteorological situation (e.g. 1903 – 156.5 mm/ day, 1916 – 108 mm/ day, 1918 – 115.8 mm/ day or 1925 – 93.2 mm/ day). It is also necessary to draw attention to the position of meteorological station – higher altitude and certain distance from both basins – so data may not be entirely correct, because situation (especially in case of convectional rainfalls) can be different at the peak and in the valley. Better results of triggers should come from intensity of precipitation from radar images (Bollschweiler & Stoffel, 2010).

Granulometric analysis specifies genesis of most active accumulations. Sorting of these is very poor in the whole parts of active zones and representation of several fractions (from clay to gravel) is also typical, which correspond with fact, that debris flow accumulations are – against slower fluvial sedimentation – usually poor sorted and the finest fraction with large boulders are represented (Pérez, 2001; Pierson, 2005). Pursuant the results of analysis, the main process which controls the movement of material of debris flow accumulation is so-called firehose effect (Larsen et al., 2006), which means a reactivation of older deposits directly in channels. In the Řehucí, the upper part of channel is not so active (according to initial vegetation and several young trees in channel), sorting is very poor (but not as poor as in the lower part) and clay fraction (minimum value in the whole active zone) was probably redeposited further downstream. There are no essential new sources areas (only small colluvial fans on slopes), which confirms that the firehose effect is responsible for formation of new DF accumulations in both studied valleys, but also in the most of recent DF accumulations in the Moravskoslezské Beskydy Mts. (Šilhán & Pánek 2010). Relative low percentage of clay fraction in both channels – untypical for DFs – may be explained by continuous redeposition to the lower parts of valley and some studies confirm that in several cases, sand fraction prevails (Wieczorek et al., 2000) and clay fraction is less than 5 % (Corominas et al., 1996). In the Jatný, we can observe less active zones and also fewer accumulations than in the Řehucí. This is due to different lithological conditions, when more resistant rocks are not so weathered as in the Řehucí (the evidence is even in lower density of river network). Active zone is accompanied by stable isles or bars and the process of firehose effect is obvious especially in lower parts of active area, where slope gradient increases and channel is filled only with DF accumulations (Fig. 3B, 3D).

In both valleys there is significant influence of basin forest covering, which could affect supplying sediments to the channels. Due to intensive clearance from 1950s to 1980s the role of vegetation in this period decreased, compared with the 1st half of the 20th century and the last 30 years (Fig. 9). Therefore debris flows could occur even with lower precipitation or with spring melting of snow such as in 1967, but in recent or before 100 years could not originate in the same conditions because of retention function of trees. According to Bovis & Jakob (1999) we can distinguish transport-limited basins, in which unlimited amount of sediments feed debris flows and are primarily controlled by hydrological and climatic conditions. This can be an example of recent behavior of both studied valleys. Supply- or weathering-limited basins are controlled by amount of sediments and substantial period must elapse before the next debris flow occurs. Thus basins should behave in the years of less vegetation cover (1950s – 1980s), when amount of sediments (eroded from slopes and gorges) had the most important role for initiation of debris flows.

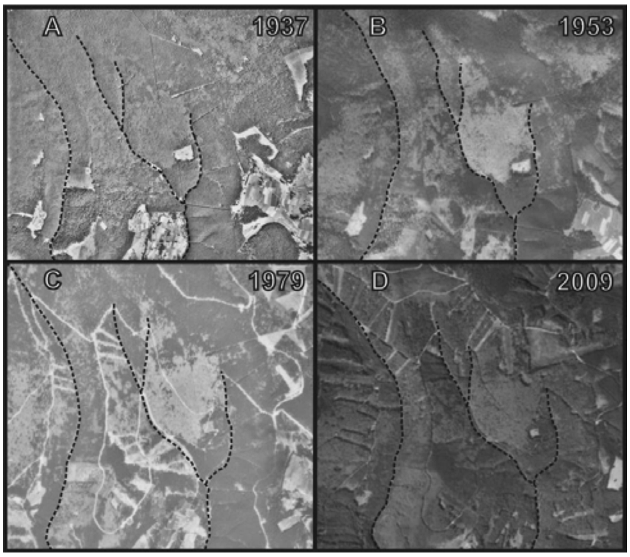

Figure 9. Forest cover of both studied valleys in selected years. Decrease is obvious from 1950s to 1980s due to deforestation and air pollution (dashed line – streams).

6. CONCLUSIONS

Occurrence of debris flows was studied in detail in the culmination part of the Moravskoslezské Beskydy Mts. It is obvious, that these processes appeared both in the past and currently, as evidenced by older deposits such as high terraces and recent active accumulations and lobes at the bottom of the valleys. Dendrogeomorphic analysis has proved to be an effective method for reconstruction of mass movement processes in high-gradient channels. Seven debris flow events based on analysis of 33 samples of disturbed trees were found in the Řehucí, five debris flow events from 15 samples were identified in the Jatný. Probably the most catastrophic events in the last 100 years occurred in 1997 and 2000 when extreme precipitation triggered the movement of material in channels. Except of rainfalls, the second trigger which is responsible for debris flows is fast spring melting of snow (detected in 1967). The results from grain-size analysis show on the nature of debris flow deposits. In most cases current debris flow occurrence is connected with reactivation of material filling the bottom of channels (so-called firehose effect), because geomorphological mapping did not confirm significant source zones of material. Also vegetation cover played an important role in triggering of debris flows in both valleys. Deforestation in the half of the 20th century enabled increased erosion from slopes and debris flows can initiate even in such meteorological conditions, in which nowadays would not occur due to full forest cover. It turns out, that using of tree ring analysis together with other geomorphic methods, brings comprehensive evidence of rapid channel processes in high-gradient streams and extends knowledge about slightly neglected parts of the landscape.

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