SPATIO-TEMPORAL ACTIVITY OF MASS MOVEMENTS IN THE KRUŠNÉ HORY MOUNTAINS (CZECH REPUBLIC): DENDROGEOMORPHOLOGICAL CASE STUDY

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ABSTRACT

This article utilizes dendrogeomorphology to investigate the spatial and temporal variation of mass movement dynamics on south-east-facing slopes of the Krušné Hory Mountains, an area affected by open-pit mining. It is based on 93 samples collected from 35 disturbed *Fagus sylvatica* trees. These samples were taken in five model locations, representing the most problematic sections of the entire area. For reasons of sample depth, the analysis was limited to the period from 1900 to 2006. The article focuses on growth disturbances such as eccentric growth of annual tree-rings and abrupt growth changes. The strongest disturbances were most commonly found in trees located near the base of the mountains, where growth disturbances has occurred periodically, since 1900. To analyze past mass movement dynamics, we introduce a "creep rate", defined as the proportion of eccentric tree-rings per decade. The results clearly demonstrate that "creep rates" culminated during the period from the 1940s to the 1970s, as a result of deep-seated slope failure the developed during the 1950s near the foottoe of the mountains.

Key words: dendrogeomorphology, tree-ring analysis, mass movements, creep, Krušné Hory Mountains

1. Introduction

The research locality is situated in the Krušné Hory Mountains, an area that has been markedly transformed by anthropogenic activities, primarily connected to brown coal mining. Such mining is done here in open-pit mines, which exploit the overburden from the area of Most Basin. During the 1980s, the open-pit mine reached the foot of the Krušné Hory Mountains and scientific literature began discussing the negative influence of mining on local slope stability (Rybář 1981; Marek 1983; Kalvoda et al. 1990; Kloss 1994; Rybář 1997). According to Hurník (1982), the removal of 400 hundred million tons of overburden per year (in 1970s and 1980s) could have caused the elastic lifting of the mountain massif and the destabilization of the upper part of the slope. To verify this speculation, in the spring of 1983, the entire area came under the observation of a special levelling circuit, Z_2b 11, which connected planation surfaces along the top of the Krušné Hory Mountains with the Jezeří Castle area and the foothills of the Krušné Hory Mountains (Kalvoda et al. 1990). Vertical movements of the earth's surface have been observed at geodetic points in two different locations. Kloss (1994) confirms this and, on the basis of a finite element method (FEM) analysis, predicts not only continued uplift, but also gravitional movements of crystallinic towards the basin.

The results of this study build upon previous dendrochronological research conducted near Salesius Hill, which is about 14 km west of this study's location (Vilímek et al. 2002). Although dendrogeomorphology is worldwide method used for reconstruction of the beginning, duration, scope and frequency of many geomorphological processes (Alestalo 1971; Braam et al. 1987a,b; Strunk 1997; Bodoque et al. 2005; McAullife et al. 2006; Stoffel et al. 2005; Stoffel 2006; Stoffel and Perret 2006 – within the area of the Czech Republic, we cite the research of Fantucci et al. 2000; Daňhelka 2001; Vilímek et al. 2002; Burda 2008; Klimeš et al. 2009; Šilhán 2009; Šilhán 2010; Žížala et al. 2010 and Pánek et al. 2011), this method have never been used in the study area.

The aim of this study is to indentify places and periods of potential mass movement developments and to verify assumptions concerning low stability ratios, as a result of open-pit mining, as well as the destabilization of upper parts of the slope. The study also refers to a reference curve, which was compared with precipitation amounts from the Czech Hydrometeorological Institute's (CHMI) Boleboř meteo-station.

2. The Study Site

The study site is located in the Krušné Hory Mountains in the Kateřinohorská Vault area. The location is situated on a south-east facing slope between Mt. Jezerka (707 m a.s.l.), Mt. Jánský (739 m a.s.l.) and Jezeří Castle (colour appendix Fig. 1). The geological characteristics of this part of the Krušné Hory Mountains have been described many times (Bárta et al. 1973; Škvor 1975; Rybář 1981; Marek 1983; Horáček 1994; Marek 1994; etc.) as have the geological conditions of the Most Basin (Rybář 1981;

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Malkovský et al. 1985; Zmítko 1983; Žižka and Halíř 2009; etc.). Král (1968) gives a geomorphic overview of the upper parts of these mountains and Vilímek has published the results of detailed geomorphic mapping of Kateřinohorská Vault (Vilímek 1992; Vilímek 1994; Kalvoda et al. 1994; Stolínová and Vilímek 2002).

The core of this vault consists of orthogneisses, which are adjacent to a series of crystalline shales the foliation of which inclines fanwise to the basin with an inclination of more than 50°, in rare cases even more than 70° (Marek 1983). It is interrupted, in many places, by numerous faults, primarily in a north-west to south-east direction (Škvor 1975). This system of faults also occurs at the top areas of the massif (Marek 1994; Vilímek 1994). These fractures divide the mountain massif into a system of blocks (Marek 1983).

The basin's sediments are composed of the underlying complex, coal seams and the overlying complex. Stratigraphically, these are heterogeneous units with various Tertiary complex sediments (clays, sandstones, sands) and Cretaceous sediments (quartzite, sandstones, calcareous clays, marlites, limestones) (Malkovský et al. 1985).

Quaternary sediments primarily include coarse-grained gravel, sandy gravel and clays with crystalline fragments. The thickness of these sediments varies from 0.1 m to 40 m. Increased thickness is characteristic in the area of alluvial cones of former tributaries (Vesnický Brook, Šramnický Brook and Černický Brook). The alluvial fans consist mainly of coarse grained gravel, sands, loam and fragments of crystalline. The highest thickness of Quaternary sediments (up to 70 m) is located under the structural slope of Mt. Jezerka and consists of the material of a Würm rockslide (Rybář in Kalvoda et al. 1994). Špůrek (1974) estimates the total volume of this rockslide at 25 milion m^3 with a total surface area of 63.5 ha. The head scarp is located on a 30° to 40° steep slope between Mt. Jezerka and Mt. Jánský about 500 to 650 m a.s.l. (Zmítko 1983). Kalvoda et al. (1994) suggested that the rockslide was triggered by an earthquake. Although most of the large accumulation was extracted during the 1970s and 1980s, the forefront of this accumulation is still morphologically distinct.

3. Material and methods

This investigation of spatial and temporal mass movement activity in the Krušné Hory Mountains is based on a dendrochronological analysis of GD in extracted samples of *Fagus sylvatica* trees. "A visual inspection of the tree-rings will in no case allow determination of the process that was causing the disturbance. Therefore, a detailed identification of geomorphic processes present at the study site as well as an accurate identification of features related to previous events imperatively need to proceed the sampling of increment cores or cross-sections in the field as well as their analysis and interpretation in the laboratory" (Stoffel and Bollschweiler 2008: 192).

In this regard, we needed detailed geomorphic mapping data on the study location. Vilímek (1992) mapped the study site at a 1 : 25,000 scale in 1992. However, because it is an area with extensive anthropogenic influences, this map has been modified according to its original methodology (see Vilímek 1992). In updating this map, we focused primarily on the foothills, where the biggest changes in relief occurred. In addition, the historical extent of the open-pit mine was determined, according to ortho-photographs from 1952, 1975, 1987 and 2008. We defined the positions of former slope failures using a Czech Geological Survey – Geofond on-line application and relevant technical reports.

3.1 Sampling strategy

Figure 1 (colour appendix) shows the positions of all of the 35 sampled trees. In order to include the oldest possible events, we selected the oldest trees. European Beech (*Fagus sylvatica*) was found in all of the selected areas. Incremental drills 700 and 500 mm long were used for taking samples. Samples were extracted at the height of stem curvature, whenever possible, otherwise at breast height (~130 cm). The 3D position, macroscopic stem defects (tilted stem, hollow trunk, stem curvature, etc.), local morphology and position of each sample were recorded (Stoffel et al. 2005).

Two or three samples were taken from each tree. In general, sample A was taken upslope sample C was taken in the opposite direction (downslope). Sample B was taken perpendicularly to the previous samples. Two samples were taken from trees distinctively tilted in only one direction. Where we could not clearly determine the dominant direction of stem declination (i.e. an S-form trunk), all three samples were taken. This sampling strategy enabled us to gather accurate information concerning possible eccentricity or loosening of tree-rings during various phases of tree growth (Braam et al. 1987b).

For the research itself, we selected trees showing visible GD. The following conditions applied, in this case:

1. Growth anomalies shall be demonstrably caused by the researched phenomenon (mass movement in this case).
2. We shall select the dominant and co-dominant trees in a given location (thereby eliminating growth signals caused by competitive effects and acquiring a longer historical range).

During the research, we excluded more inclined trees growing on the erosion slopes of brooks. In this way, we eliminated trees, whose stem inclination was caused by the erosion activity of mountain brooks. We also excluded trees growing in the immediate vicinity of roads, which undercut the slope in several places. Also, we excluded trees, whose stems were damaged by corrasion in a possible drilling spot, from the research.

3.2 Sampling sites

In accordance with the geomorphic mapping, we selected five different locations in the study site (groups A–E; colour appendix Figs. 1 and 2). Three sites are located at the foothill near the open-pit mine mine. The two remaining sites are higher on the slope at locations where historical vertical movements of points on a Z_2b 11 levelling circuit have been observed. We therefore analyze each part separately:

Group "A": The first six trees selected are located on a gentle slope (15°) at the foot of the structural slope of Mt. Jezerka. The location is not in the immediate vicinity of the open-pit mine but it is along an edge of the accumulation area of the Würm rockslide. Some rocks are scattered in a pattern of rock debris higher on the slope. These fragments of crystalline can reach one to five metres in size. The current thickness of preserved Quaternary sediments (after excavation) under the slope of Mt. Jezerka is estimated to vary between 30 and 40 metres.

Group "B": This location is very close to the mining activities. Some trees grow mere metres from the edge of the overburdened benches of the open-pit mine. A typical anthropogenic slope fluidly transitions into the structural slope (27–35°) with numerous rock outcrops, rock debris and erosion scars. In the Šramnický Brook valley, the slope decreases significantly (less than 15°). Morphologically, a talus cone, composed of gritty deluviofluvial sediments, dominates. Tilted and curved trees as well as soil ripples and ridges indicate slow creep of colluvium over bedrock outcrops. We analysed 16 trees in this location and, due to the terrain morphology and the extent of anthropogenic activity, we expect the biggest GD to be found here.

Group "C": In the geomorphologically distinct structural slope under the Castle complex, we found only two trees that were appropriate for this dendrogeomorphologic research. The slope has an inclination from 30 to 35° and is composed of a solid gneiss rock, which is sparsely covered by a layer of colluvial debris. Historically, part of the castle Arboretum (since the end of the 17th century) was located here, but it was clear cut in the 1980s, limiting the number of available trees at this site.

Group "D": This group of trees was also selected from the structural slope above the castle complex. We include these trees in the research, because of the vertical movements of Z_2b 11 geodetic points during the 1980s. The slope's gradient is over 35° and the selected trees grow on a ridge that is a relict of the original structural slope which, to the south-west and north-east, has become steep erosion-denuding slopes. This site has a number of rock outcroppings and rock faces. We selected five trees from this location.

Group "E": The last six trees were found on the slope of Mt. Jezerka where, as in the previous case, movements of the points of a Z_2b 11 levelling circuit were observed. The location is characterized by a 40° erosion-denuding slope that gradually transitions into the more moderate edge of Mt. Jezerka's peak (15–20°). Morphologically, the site includes dominant products of periglacial processes, such as frost cliff rock towers and rock outcroppings.

3.3 Tree-ring analysis

To complete the tree-ring analysis of our samples we used Past4 software (SCIEM) and a TimeTable measuring device, which gave exact measurements of the width of tree-rings to the nearest 0.01 mm (Fig. 4). We assessed the eccentricity of individual tree-rings in given year and any abrupt growth changes. When trees exhibit eccentric growth in a particular year, we can assume that tree inclination is occurring. To confirm eccentric growth patterns, we compared samples B and C or A and B (depending on the direction of stem inclination or stem curvature; equation 1).

We used tree-ring analysis of the samples taken from particular trees to determine the eccentricity of each year (E_i). In 1971, Alestalo (1971) proposed a method for the numerical calculation of eccentricity. Braam et al. (1987a) modified this formula:

$$E_i = (RC_i - RB_i) / (RC_i + RB_i) \text{ or } (RA_i - RB_i) / (RA_i + RB_i) \quad (1)$$

E_i = annual eccentricity of a tree-ring,
RX_i = width of a tree-ring in the respective direction.

In this study, we modify Braam's formula to be applicable for deciduous trees, which form reaction wood on the opposite side, in comparison with coniferous trees. Braam et al. (1987b) speculate that, during its growth, a tree can be influenced by mass movements with differing dynamics and direction. When an analysed tree showed macroscopic signs of different inclination, we determined E_i from all three samples (Braam et al. 1987b). By simply plotting the E_i values in a graph, we obtain linear data, from which the running inclination of a tree over the years can be read.

According to their E_i values, we divided tree-rings into three categories: slightly eccentric (E_i 0.1–0.3), medium eccentric (E_i 0.31–0.5) and highly eccentric (E_i > 0.5) (Burda 2008; Žížala et al. 2010). We then weighted the observed eccentricities, on the basis of their E_i value; i.e. E_i values between 0.31 and 0.5 received a weight of 0.5 and tree-rings with E_i values greater than 0.5 were weighted with a factor of one (Daňhelka 2001; Klimeš et al. 2009).

The percentage of trees showing inclination in a given year can aid in analyzing temporal variability of mass movement in the area (Braam et al. 1987a). This variability can be expressed with an index number (I_i), calculated for each year (equation 2):

$$I_i = (\Sigma R(k)_i) / (\Sigma A(k)_i) \times 100\% \quad (2)$$

I_i = is index of activity in year i,
$R(k)_i$ = trees inclined in a particular year i,
$A(k)_i$ = examined trees in a particular year i.

Fantucci (1999), Daňhelka (2001) or Žížala et al. (2010) also use this formula. It indicates the percentage of tree-rings which show eccentric growth in a given year. By recording the values in the graph, one can easily describe the temporal variability of mass movements in a particular year.

We analysed the spatial and temporal distribution of eccentric tree-rings by decade using a Geographical Information System (GIS). Data on sample trees (their position and I_i index value per decade) were transformed into geo-objects to enable the spatial visualization of GD. We used Surfer 9 (Golden Software) to investigate the data and, in particular, to examine spatial relationships between all the trees. Linear interpolations (grid size 30 × 30 m) including data from five decades (1900–1919, 1920–1939, 1940–1959, 1960–1989 and 1990–2006) were performed (Stoffel et al. 2005).

The study also evaluates abrupt growth changes between individual tree-rings. According to Fantucci (1999), these growth changes were divided into six categories. Categories S1 through S3 (S1 = 40–55%, S2 = 56–70%, S3 > 70%) describe growth suppression, while R1 through R3 (R1 = 50–100%, R2 = 101–200%, R3 > 200%) describe release of growth. These GD indicate tree reactions to a specific change in the surrounding conditions. For example, a tree might react to trunk damage due to rockfall or root system damage connected to a shallow landslide by suppressing growth.

Abrupt growth release generally results from a decrease in competitive stress due to the removal of surrounding vegetation. Abrupt growth changes can also be caused by a change in the conditions of a particular location (for example atmospheric precipitation, nutrients). To correctly interpret these changes it is necessary to compare the assessed samples with a reference curve and rule out any impact of unusually dry or extremely rainy years. Very similar to the analysis of eccentric tree-rings, we calculated the I_i index for S_X and R_X categories, which characterise proportion of GD in a given year.

3.4 Reference chronology

A fundamental element of any dendrogeomorphological research is a reference curve, which is essential for identifying GD that occur independently of the slope movement activity (Stoffel and Bollschweiler 2008). This is why the selection of suitable trees is so important. In selecting trees for this study, we followed these guidelines (Principles of correct procedures for the selection of suitable trees can be found in the comprehensive works of Cook (1985), Cook and Kairiukstis (1992), Stoffel (2005) or Janda (2008):

1. select trees growing in the vicinity of the researched location,
2. do not observe growth disturbances at a researched tree,
3. choose dominant trees, solitary if possible.

We retrieved 15 samples from trees growing in near the study site. The selected trees should not be afflicted by mass movements and, consequently, records from these trees can be used to eliminate local influences or errors encountered during evaluation that could distort the results. We used ArsStan software (Cook 1985) to create a local non-detrended reference curve. Using this reference curve, we can determine whether GD could have been caused by climatic influences (mainly by dry years). We used data from the CHMI (Czech Hydrometeorological Institute) climatologic station in Boleboř to evaluate precipitation amounts. The station is situated in the mountains about seven kilometres northwest of Jezeří Castle at an altitude of approximately 640 m a.s.l. The location of this station is not ideal, in regards to the study area, but other local climatologic stations either have much shorter historical records or lie outside the Krušné Hory Mountains. Data records from the Boleboř station date back to 1955. We created graphs of annual precipitation; precipitation during growing season and precipitation in April to June were created from climatic data.

4. Results

Figure 5 shows an updated geomorphic map. No recent landslides or rockslides were found during the remapping of the mountain region (recent landslides occur in the basin – Burda et al. 2011). Former slope failures (from 1952 and from the Würm period – see in colour appendix Fig. 2), found with the CGS – Geofond on-line application, are now indistinct due to the advancement of the open-pit mine along with ground works. Based on the morphology as well as visible GD (tilted and "pistol-butted" stems dominate; Tab. 1), we estimated that the creep of a colluvial mantle is now the dominant geomorphic process at the sampling sites.

4.1 Growth disturbances

Figure 6 (colour appendix) presents the main results of this dendrogeomorphological study. We divided eccentric tree-rings into three groups, according to E_i value: slightly eccentric, medium eccentric and highly eccentric. We also calculated an I_i value for each year. Figure 6A clearly shows periods of increased I_i values. These include the years 1903, 1904, 1906, 1909 through 1911, 1914, 1923, 1927 and 1928. There is also an observable increase in values, beginning in 1955 and culminating in the years 1957 through 1964, 1967 through 1969, 1972 through 1974, 1981, 1985, 1992 and 2004 through 2006. On the other hand, 1901, 1915, 1925, 1936, 1937 and 1942 are years that exhibit minimal production of eccentric tree-rings.

The increase in I_i values is particularly notable after 1955 only dipping below 40% in six of these years. This is due to the trees from group "B", within which the strongest GD were observed, after 1940. To be able to more accurately identify years in which the dynamics of mass movements could have been more intensive, we conducted various assessments of tree-rings (from group "B") with high and medium eccentricity, weighting them appropriately (Fig. 6C). It is clear that the largest disturbances happened between 1959 and 1961 and between 1972 and 1974. An overall increase in observed GD is also evident after the mid 1940s.

Tab. 1 Different types of macroscopic stem defects observed during the research

Visible defects	
tilted stem	19
stem curvature:	
– "pistol-butted" form	*12*
– "S-form"	*4*
total	**35**

Our research focused on abrupt growth changes (primarily on growth suppression) that demonstrate changes in the conditions of a given location. We divided GD, such as suppression and release, into six categories: S1 through S3 and R1 through R3. In the event that a tree produced an eccentric tree-ring in a given year, sample B should show sudden growth suppression caused by impact of this eccentric growth. In the graphs, such years should be the same as those years, in which eccentric tree-rings emerged. Figure 6B shows I_i index values for tree-rings that exhibit abrupt growth suppression. In particular, the years 1914, 1928, 1934, 1940, 1958, 1960 and 1961 correlate well with strong years of eccentric growth (Fig. 6A). Eccentric tree-rings likely emerged, during these years, causing growth suppression in sample B.

Because atmospheric precipitation (especially during the growing season) is one of the key factors influencing the growth and width of tree-rings, we tried to explore the ways, in which precipitation variations in the observed location influenced the creation of tree-rings. Figure 7 illustrates the amount of annual precipitation, precipitation during the growing season (April to June) as well as precipitation during first months of the growing season (April and May). Different interannual precipitation amounts are another factor influencing the growth of annual tree-rings. In periods when we observe the greatest differences in precipitation amounts between two years, we can also expect to find the greatest abrupt growth changes.

To shed light on vegetation's reaction to precipitation extremes as well as to interannual precipitation differences, we compared critical years with the reference curve visually. This demonstrates that the vegetation reacts sensitively to low precipitation amounts or to distinctly lower interannual precipitation. This is quite clear in 1982 and 1985 when low increments correlate well with subnormal annual precipitation, as well as in 1968 and 1988 when low increments coincidence with subnormal precipitation during the growing season or April–May, respectively (Fig. 7). Therefore, we can claim that the majority of suppression GD in the reference curve are caused by climatic effects. On the other hand, we detected no distinct growth changes during years exhibiting significant interannual precipitation amounts or above-average precipitation.

If we compare the reference curve with a graph of growth suppression visually (Fig. 6B and 5D), we find that the two are similar only in 1926 and 1928. Therefore, in the study area, the majority of suppression GD that we discovered are connected with non-climatic factors (trunk tilting resulting in eccentric tree-ring growth).

4.2 Spatio-temporal distributions of growth disturbances

We also tried to find locations and decades exhibiting accelerated creep movement as well as places of repeat activity. Therefore "creep rate" was defined to determine the dynamics of past mass movements. The "creep rate" was defined as the proportion of eccentric tree-rings per decade (1900–1919, 1920–1939, 1940–1959, 1960–1979, 1980–2006). This is based on the notion that more GD (eccentric tree-rings) indicate a creep acceleration or longer lasting activity in an observed decade. We analyzed medium and highly eccentric tree-rings separately. Figure 8 (colour appendix) describes the spatio-temporal distribution of "creep rates". The figure shows that eccentric tree-rings occurred during the period from 1900 to 2006 in trees in all of the five analyzed groups. As in Fig. 6A and 6C, we can observe an increasing proportion of highly eccentric tree-rings since the 1940s and 1950s.

The spatial pattern reveals that the site of group "A" was less frequently disturbed by mass movement than the other locations. In contrast, the highest "creep rates" occurred in group "B". More than 80% of the tree-rings in two trees from this group were eccentric ($E_i > 0.31$) during the 1940–1959 period. During the period from 1960 to 1979, there were even two trees showing more than 90% eccentric tree-rings ($E_i > 0.31$). A similar trend is evident in lower picture which shows the proportion of highly eccentric tree-rings ($E_i > 0.5$). During the first decade, the proportion of eccentricities did not reach 15%, but over following decades (particularly after 1940) the proportion increases dramatically. This indicates a higher "creep rate" after 1940. A concentration of disturbed trees in the area of the Šramnický Brook's valley mouth is quite clear, during periods of greatest eccentricity (1940–1959, 1960–1979).

Open-pit mining directly affected the site of group "B" at the end of 1980s and the beginning of the 1990s. By evaluating individual E_i values for each tree, however, we realise that significant GD occurred in only four trees during this period. These are trees nos. 9, 13, 15 and 25, growing near the edge of the open-pit mine (Fig. 9). The highest eccentricities were identified during 1991 and 1992, or to a lesser degree in 1987. The highest E_i values vary between 0.45 and 0.84.

5. Discussion

Because the study area is not a landslide location, we consider the resulting GD values to be relatively high (compared, for instance, with landslide areas described in Daňhelka 2001; Klimeš et al. 2009 and Žížala et al. 2010). Because the I_i value of eccentricities reaches maximum values in the 70% range, it is clear that movements of all observed parts of the slope do not come at the same time. The spatio-temporal analysis also confirmed that movements of smaller areas within the observed location are more likely to occur. Repeat movements probably occurred in the area of group "B", where values of "creep rates" are higher than 45% (E_i > 0.31) in each of the decades studied.

The largest GD occurred between 1959 and 1961 and also between 1972 and 1974. We recognise deformations of relief caused by the impacts of previous underground mining as a possible reason for these GD (Vilímek et al. [2002] arrived at similar conclusions during a dendrogeomorphological investigation of slope deformation on Salesius Hill). Deformations culminated from 1952 to 1954, when they evolved into large deep-seated slope failure in the area of the former village of Jezeří, which was, incidentally, destroyed by this slope failure (Špůrek 1974; Marek 2006).

After 1940, the highest "creep rates" were recorded in the Šramnický Brook valley, near the 1952 slope failure. This slope failure probably caused a release of tension over the larger part of the slope and, therefore, could be the primary cause of the observed eccentricities. GD from the end of the 1950s are very likely signs of the sudden acceleration of subsequent Quaternary colluvial and proluvial sediment creep movements. During 1958, an above-average precipitation year, disrupted sediments probably became aquifers which resulted in subsequent creeping.

Similar GD from 1972 to 1974 are likely not a reaction to running exploitation because the open-pit mine did not yet extend towards the foot of the Krušné Hory Mountains. In spite of low precipitation in 1972 and 1973, the cause of the GD mentioned can be found in above-average precipitation in 1970 which, again, resulted in the destabilisation of Quaternary sediments. A similar situation occurred in 1974 when abnormally high precipitation was followed by disturbances in 1975 and 1976. The following years of average precipitation caused settling and a decrease in the occurrence of GD. On the whole, these results correspond with previous conclusions that precipitation is a triggering factor, destabilizing exposed parts of the slope (Burda and Vilímek 2010).

In general, we expected GD to be connected with the advancement of the open-pit mine. However, this theory was confirmed in only four trees from group "B" that were located near the edge of the open-pit mine. The identified GD (culminating during the 1987–1992 period) probably reflect local slope destabilization and creep acceleration resulting from mining. According to Figures 6C and 8, GD occurred in the study site before the open-pit mine reached the mountains.

Only four samples from two trees were taken from the group "C" sampling point. These trees grow on the structural slope, which is the base of the crystalline block, upon which the castle complex lies. Potential GD could indicate movements of the gneiss block, on which the Castle complex is situated. If we assess eccentricity, 1958 stands out, because the E_i index reaches high values in both cases (E_i 0.70; 0.32). Other common peaks occur in 1990–91 (E_i 0.70; 0.60) and 2000 (E_i 0.56; 0.37). The evaluation of only four samples (that were, moreover, low in quality and in sample depth) from this location presents a deficiency and it is not possible to establish precisely what factor caused significant GD or how to interpret them.

In other groups the temporal variability of "creep rates" does not change much over the decades and GD have occurred regularly, since 1900. Therefore, we can reject any connection between GD and the vertical movements of geodetic points in the Z_2b 11 levelling circuit. Beyond this, the vertical movements of geodetic points could be caused by the same factor leading to GD origin, i.e. Quaternary colluvial sediment creep which has been ongoing, at least, since 1900. Any exact determination of this lies beyond the current capabilities of dendrogeomorphology. However, we can state with certainty that GD occurred in the upper parts of the mountains before the open-pit mine was opened and that GD did not increase after the development of mining activities.

6. Conclusion

This study uses the outlined, dendrogeomorphological approach, for the first time, to analyze spatial and temporal variations in mass movements on south-east-facing slopes of the Krušné Hory Mountains. With added insights from geomorphic mapping, the results prove that creep is a dominant type of mass movement process in the study area. We successfully determined spatial variation in the "creep rate", as well as intervals of movement acceleration.

The highest "creep rates" were found at the foot of the mountains, where Quaternary sediment layers are thickest. The largest GD, recorded from 1959 to 1962 and from 1972 to 1974, did not result from mining, but as a consequence of deep-seated slope failure from the 1950s. On the contrary, we confirmed an influence of mining, in the open-pit mine, on the occurrence of GD only during the last decade and only in four trees. In addition to local morphology and slope gradient, abnormal precipitation seems to be a significant factor leading to creep acceleration and, consequently, movement dynamics are influenced by the saturation of Quaternary sediments.

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RÉSUMÉ

Prostorová a časová aktivita svahových pohybů v Krušných horách (Česká republika)

Hodnocení prostorové a časové variability svahových pohybů na svazích Krušných hor se primárně opírá o výsledky letokruhové analýzy (hodnocení excentrických letokruhů a růstových změn) 93 vzorků odebraných z 35 buků lesních (*Fagus sylvatica*). Při geomorfologickém mapování nebyly v zájmové lokalitě mezi Jezerkou (707 m n. m.) a zámkem Jezeří identifikovány recentní projevy skalních řícení a sesouvání, nicméně bylo konstatováno, že v oblasti dochází k ploužení kvartérních sedimentů.

K akceleraci těchto pohybů dochází epizodicky, zřejmě v důsledku zvodnění kvartérních sedimentů vodou. Kontinuální pohyby v celém území se neprokázaly. Největší dynamiku pohybu sledujeme v údolí Šramnického potoka od 50. let 20. stol. Primární příčinou akcelerace pohybů je vznik hluboce založené svahové deformace, která vznikla poddolováním území během hlubinné těžby. Naopak dopad povrchové těžby na akceleraci creepových pohybů byl prokázán jen na přelomu 80. a 90. let, a to pouze u čtyř stromů.

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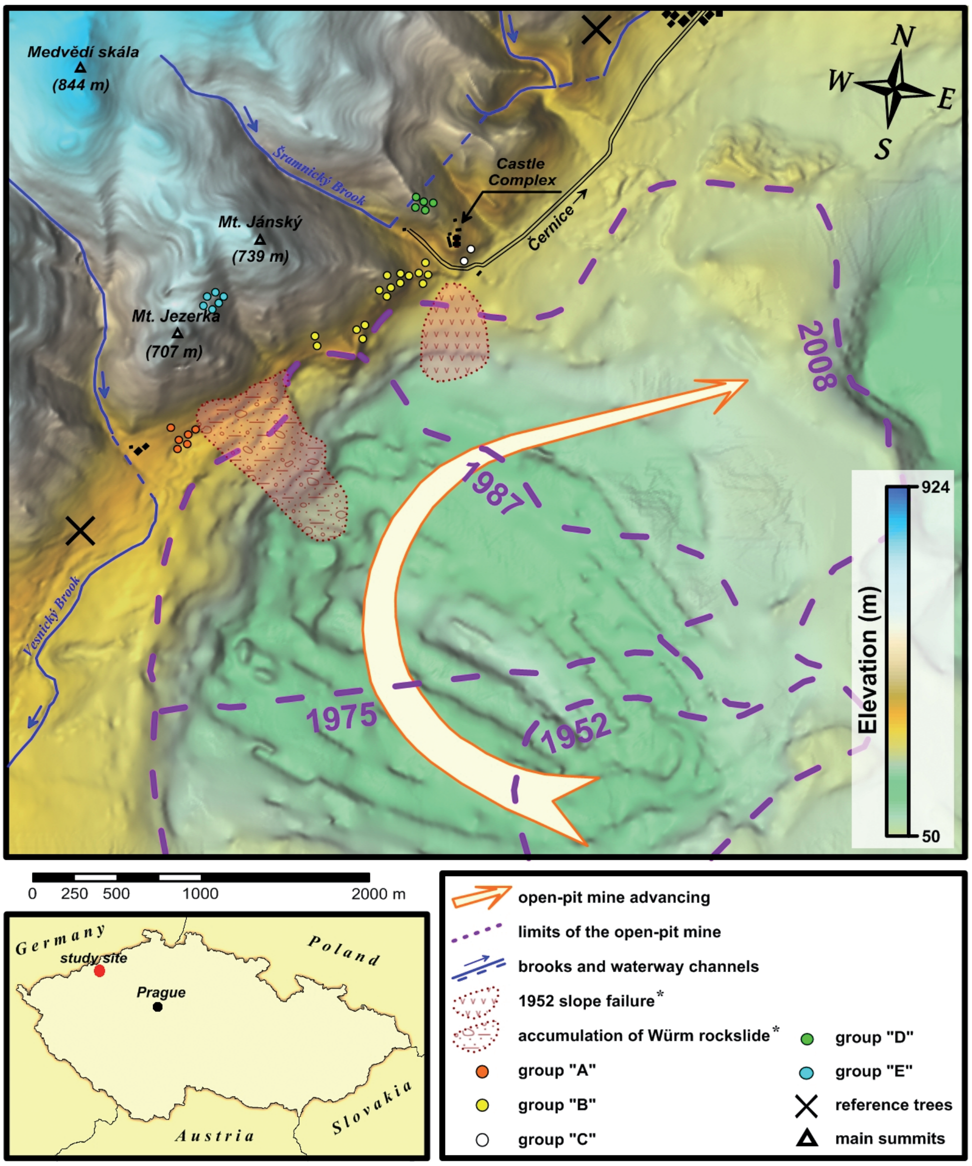

Fig. 1 The study area and its geographic setting. Locations of the open-pit mine and of the analyzed and reference trees is ndicated on the map (* according CGS – GEOFOND)

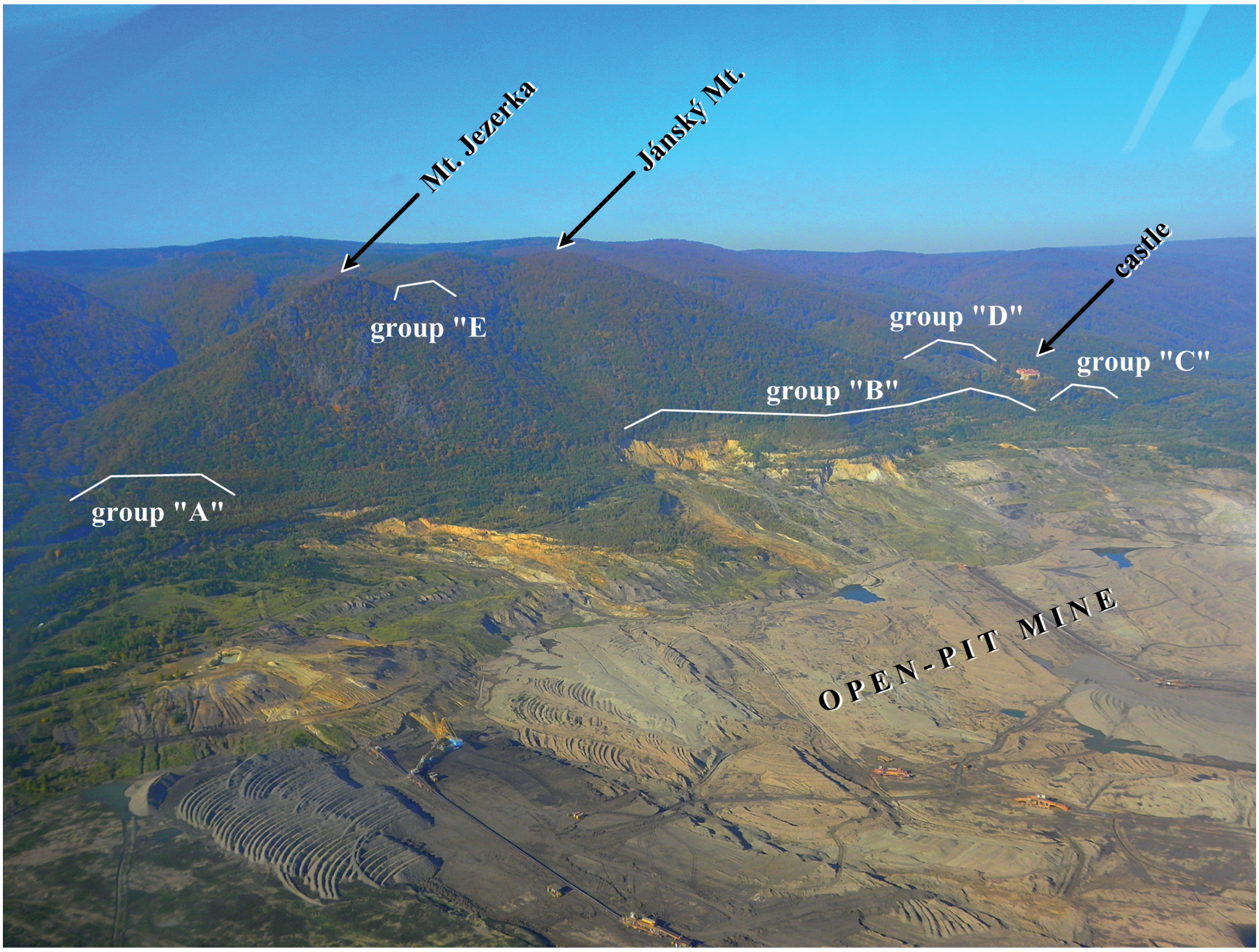

Fig. 2 Aerial view on the study area, south-east facing slope of the Krušné Hory Mts. (foto: J. Burda, 2010)

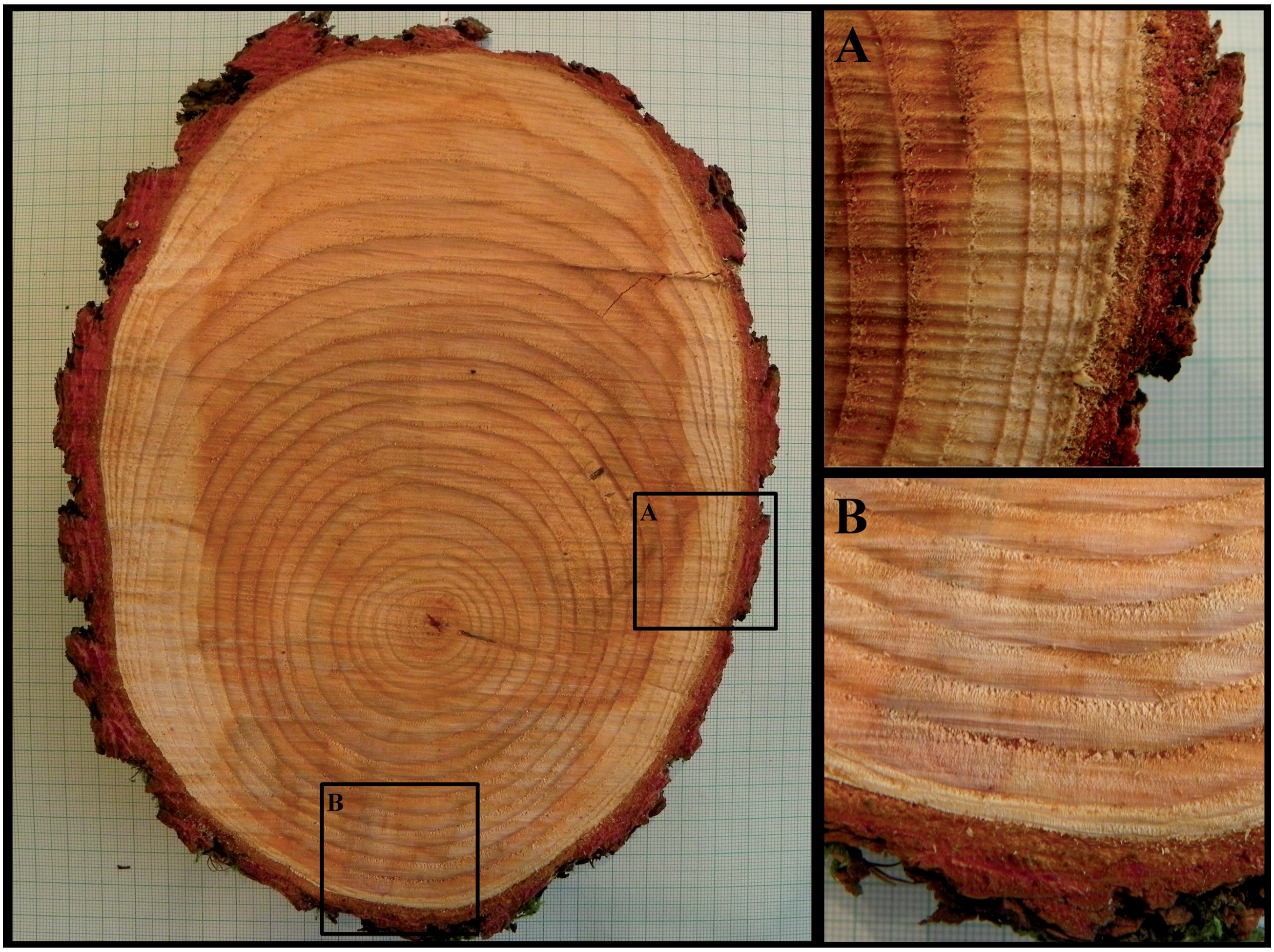

Fig. 3 Growth distubances (tree-ring eccentricity and reaction wood) on cross-section taken at the base of inclined Larix decidua. Comparison of growth suppresion in the oposite direction of stem inclination (B); and in the direction perpendicularly to the stem inclination (A)

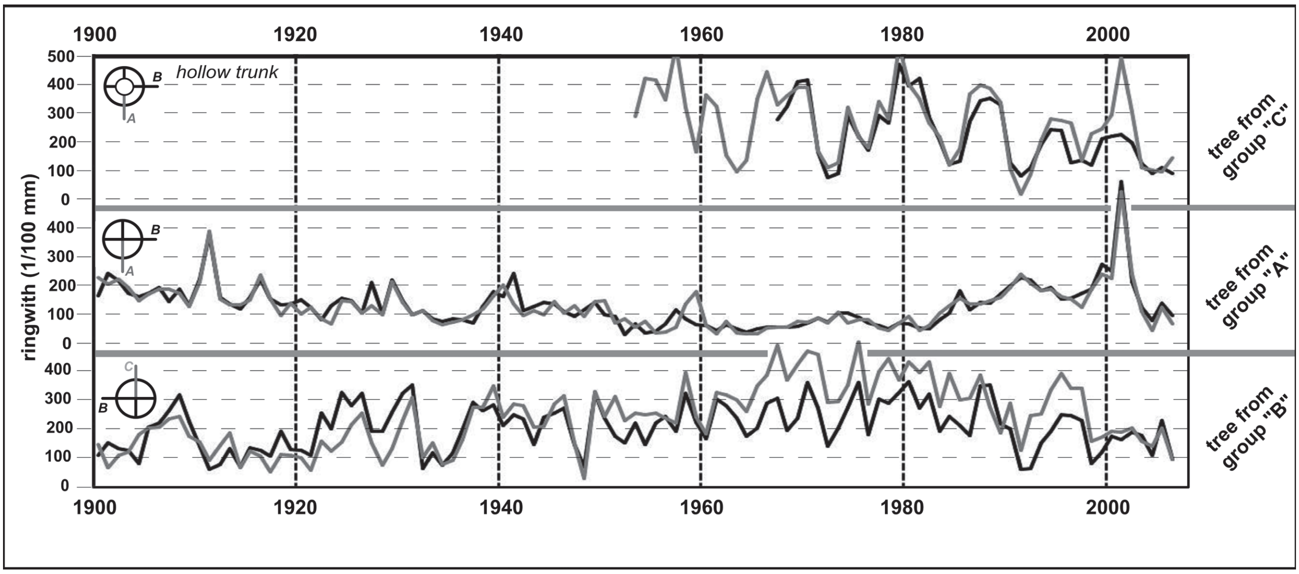

Fig. 4 Growt curves from different trees. The first depicts repeat, abrupt growth changes as a result of stem and crown breakage (top). The second is an undisturbed tree (middle). The third shows GD resulting from creep that causes the tilting of a tree (down)

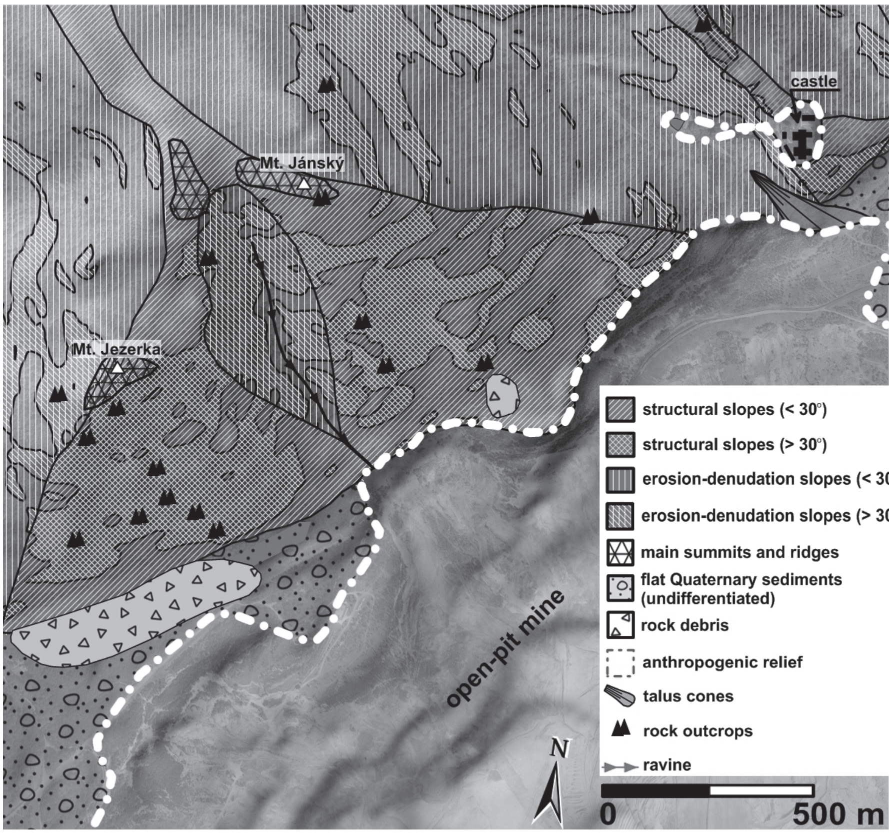

Fig. 5 Generalized geomorphological sketch map of the study site

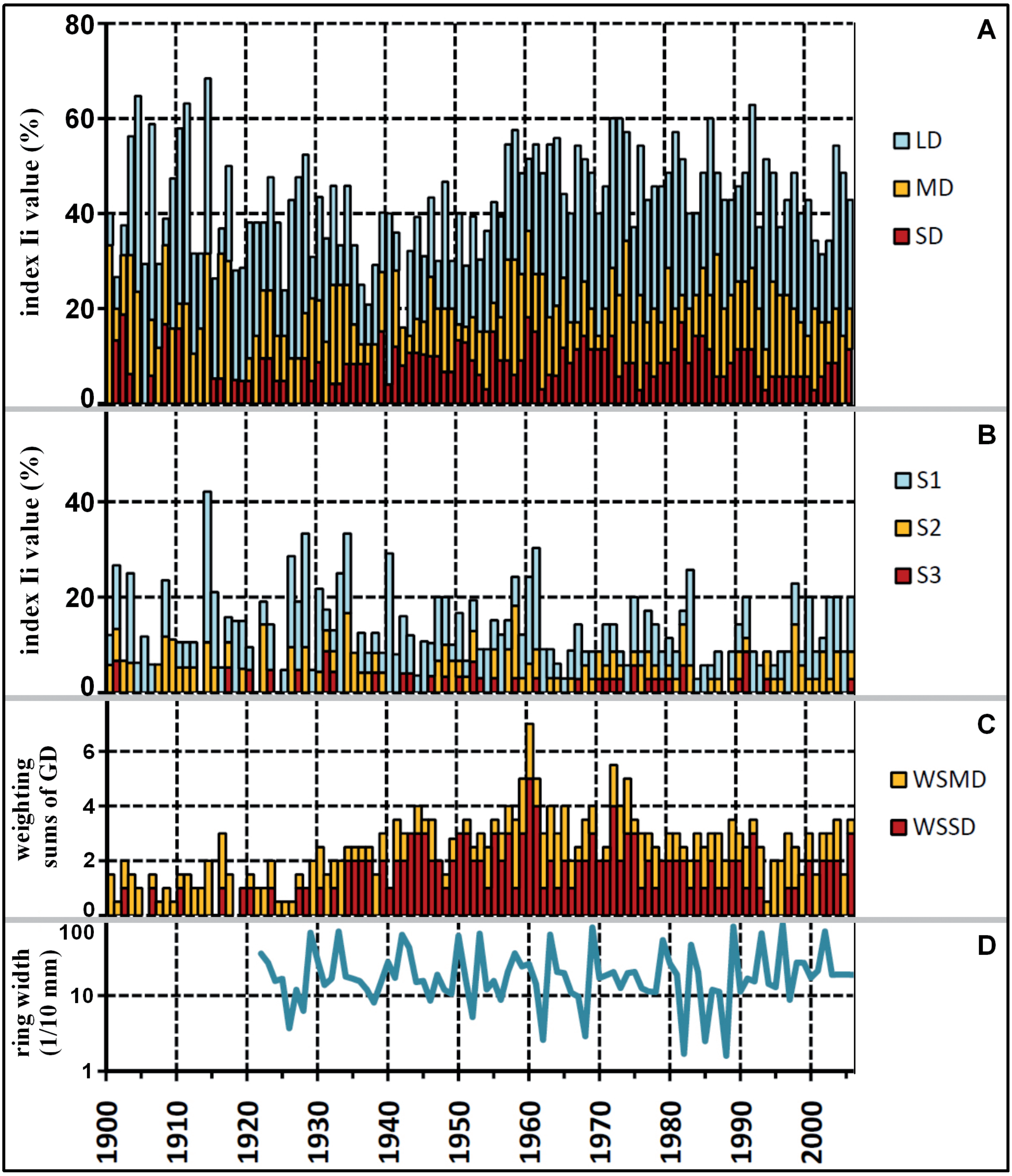

Fig. 6 An overview of primary results. (A) Ii index, describing the proportion of eccentric tree-rings, LD (Ei = 0.1–0.3), MD (Ei = 0.31–0.5), SD (Ei > 0.5). (B) Proportions of categories S1–S3 characterizing abrupt growth supression. (C) Weighted sums of eccentric tree-rings per year. Medium disturbances – WSMD (Ei 0.1–0.3) are weighted sums of 0.5 and strong disturbances – WSSD (Ei > 0.5) by a factor of 1. A separate graph was created for trees in the "B" group. (D) Local reference curve (non-det.) that was created from 15 undisturbed reference trees

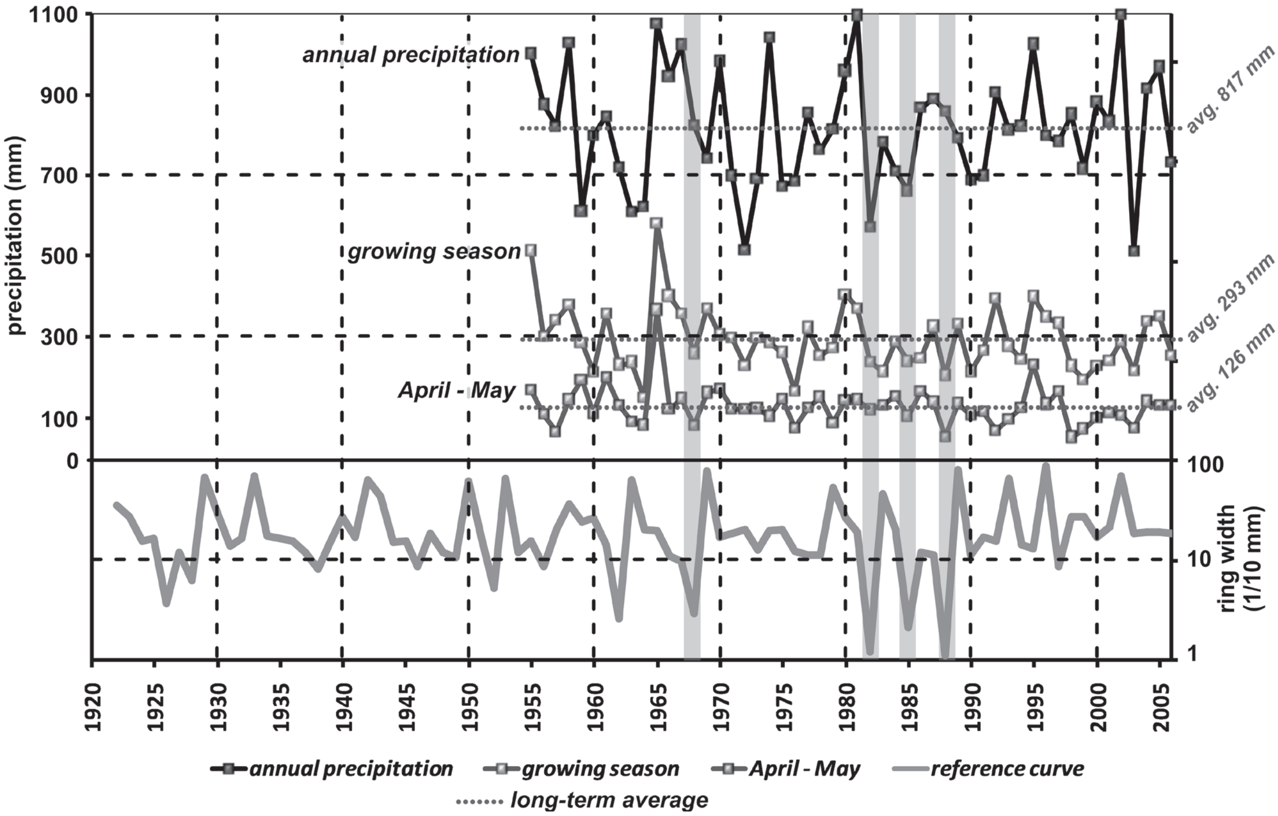

Fig. 7 Comparison of annual precipitation, precepitation during growing season precipitation in April–May and reference curve (source: Burda 2008)

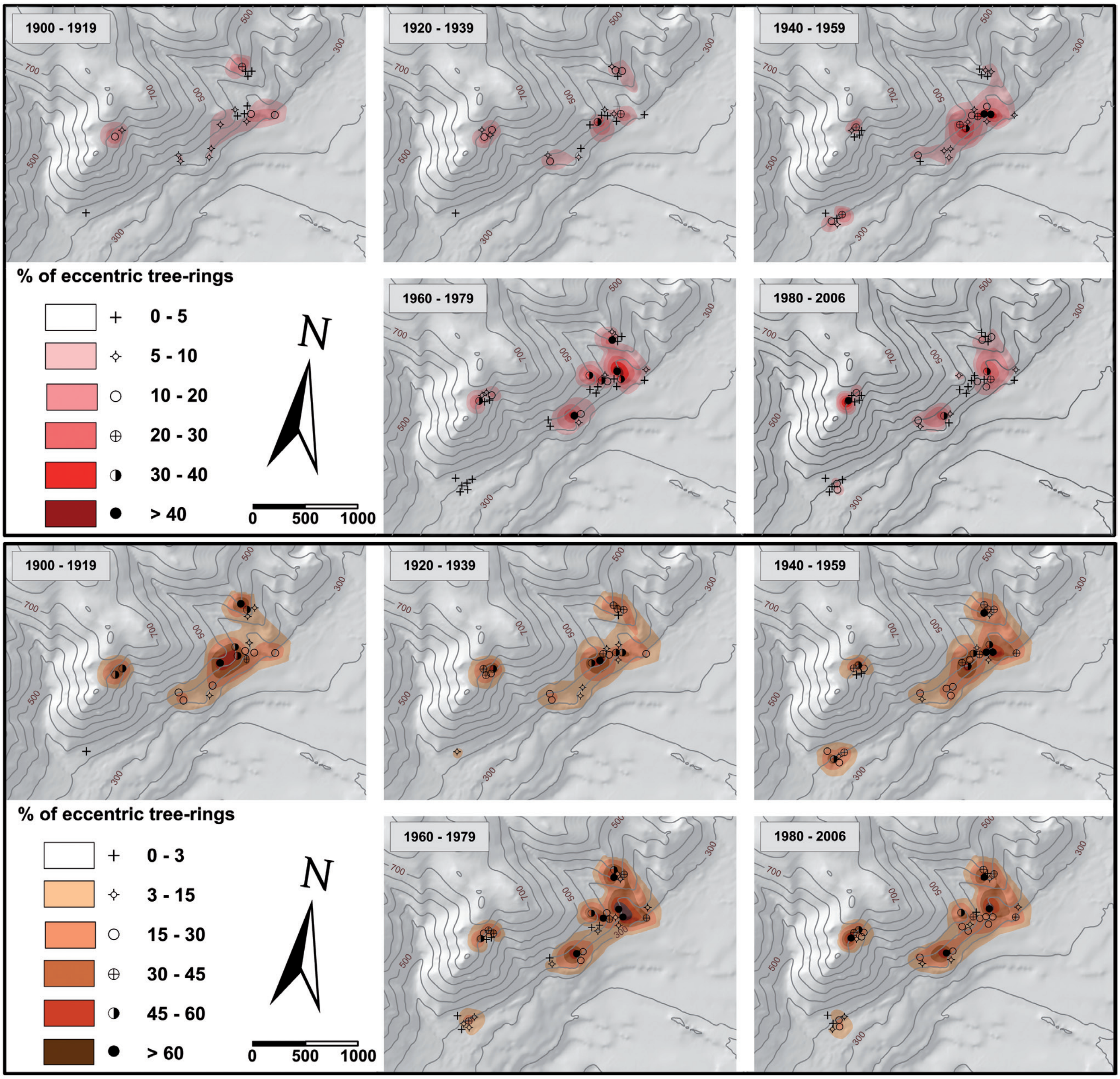

Fig. 8 "Creep rates" by decade, based on the proportion of highly eccentric tree-rings (Ei > 0.5; top) and on the proportion of mediu eccentric trr-rings (Ei > 0.31; down). The patterns have been generalized based on linear interpolation

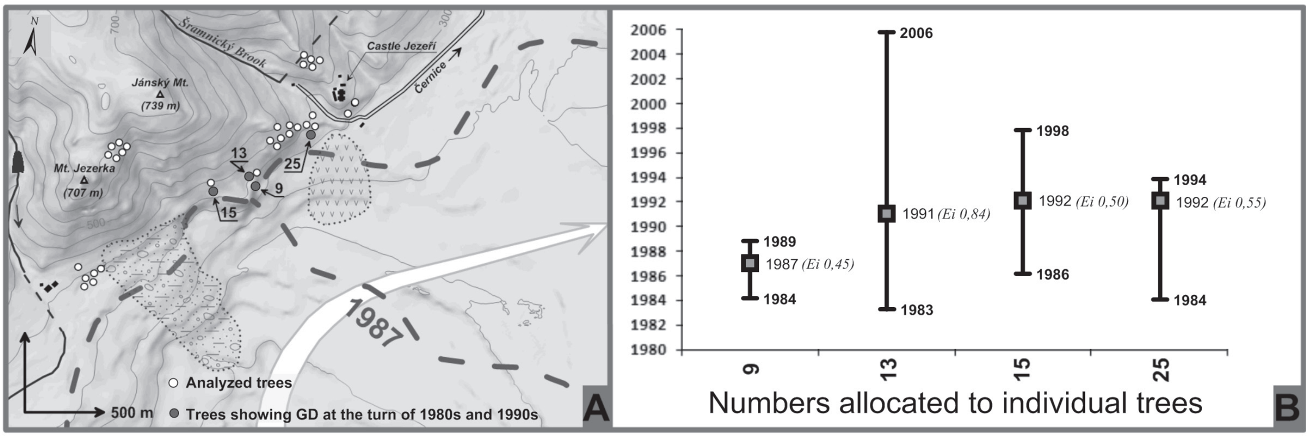

Fig. 9 (A) Position of trees exhibiting creep acceleration at the end of the 1980s and the beginning of the 1990s. (B) Duration and culmination (highest eccentricity) of eccentric tree-ring growth that was likely caused by acceleration of creep movements in relation to the mining