GEOCHRONOMETRIA 34 (2009), pp 57-66
DOI 10.2478/v10003-009-0011-7

Available online at
versita.metapress.com and www.geochronometria.pl

DENDROCHRONOLOGICAL RECORDS OF DEBRIS FLOW AND AVALANCHE ACTIVITY IN A MID-MOUNTAIN FOREST ZONE (EASTERN SUDETES – CENTRAL EUROPE)

IRENEUSZ MALIK[1] and PIOTR OWCZAREK[2]

[1] *Faculty of Earth Sciences, University of Silesia, Będzińska 60, 41-200 Sosnowiec, Poland*
[2] *Institute of Geography and Regional Development, University of Wrocław, Pl. Uniwersytecki 1, 50-137 Wrocław, Poland*

Received 26 November 2008 Accepted 17 July 2009

Abstract: Dendrochronological methods were used to determine the frequency of debris flow/avalanche events in a forest zone. A debris flow and avalanche track located in the Eastern Sudetes Mountains (Central Europe) was analysed. The length of the youngest debris flow/avalanche track is about 750 m. Three distinct sections of the debris flow can be identified along the longitudinal section: niche, gully and tongue. The dendrochronological study shows that trees started growing on the margins of the debris flow between 1908 and 1963. Hence, debris flow and/or avalanche events occurred on this slope at the turn of the 19^{th} and 20^{th} centuries. All trees collected from the tongue started growing between 1935 and 1964. However, a large debris flow event took place several years before, most probably during an extraordinary rainfall in June 1921. Following this event, several relatively large debris flows have occurred during the growing season, the strongest dendrochronologically confirmed events occurring in 1968, 1971-1972, 1991, 1997 and probably in 1977. Spring debris flow events induced by snow melt and/or avalanches have occurred in 1994 and 2004. The results suggest that with favourable geological conditions, debris flows can occur very frequently within entirely forested slopes.

Keywords: debris flow, avalanche, dendrochronology, mid-mountains.

1. INTRODUCTION

Debris flow is an event during which a large volume of a highly concentrated viscous water-debris mixture flows down a slope. Numerous studies have analyzed the causes of debris flow development. The most important factors helping to produce a disturbance of slope equilibrium and the initiation of debris flow are: rainfall (Caine, 1980, Reid *et al.*, 1988, Kotarba, 1992, Fiorillo and Wilson, 2004), snow-melt (Bardou and Delaloye, 2004, Decaulne *et al.*, 2005) and earthquakes (Lin *et al.*, 2003). The debris flow phenomenon occurs particularly frequently in high mountain environments where debris flow activity is often investigated by analysing the wood anatomy of trees (Baumann and Kaiser, 1999; Gärtner *et al.*, 2003, Stoffel *et al.*, 2005). Commonly used dendrochronological markers in this type of study include abrupt reduction of tree ring width, growth release, scars, as well as the age of adventitious roots. However, no dendrochronological studies have investigated debris flow activity located in mid-mountain areas in the forest zone. A debris flow very rarely appears if its morphological form is wholly situated within a forest zone because root systems prevent slope failures by reinforcing soil and debris cover (Abe and Iwamoto, 1986). Previous research on this type of form was mainly concentrated on analysis of the suppression of debris movement by forests and the influence of trees on the shape of debris flow (May, 2002; Ishikawa *et al.*, 2003, Lancaster and Hayes 2003).

Avalanches often occur within debris flow tracks which remove and wound trees (Malik and Owczarek, 2007). Dendrochronological studies often cover avalanche paths in order to recover particular information about past events and their timing (Carrara, 1979; Casteller *et al.*, 2008). Several indicators are very frequently

Corresponding author: P. Owczarek
e-mail: piotr.owczarek@geogr.uni.wroc.pl

ISSN 1897-1695 (online), 1733-8387 (print)

used to reconstruct past avalanche events: (a) scars, (b) tree ring reduction, (c) abrupt growth release, (d) reaction wood, (e) tree age, (f) tree mortality.

The aims of this study are (1) to identify debris flows on the basis of geomorphic forms and (2) to use dendrochronological methods to date debris flow and avalanche events along the debris flow/avalanche track.

2. STUDY AREA

General information

The study area is located in the upper part of the Černy Potok catchment in the Eastern Sudetes Mountains (Central Europe; **Figs. 1A** and **2**). The Sudetes Mountains belong to a vast medium elevation mountain system that formed during the Hercynian Orogeny, an event which produced numerous mountain ranges and isolated massifs in Central and Western Europe. The study area is built of Proterozoic and Old Palaeozoic crystalline and metamorphic rocks, primarily gneisses (Šafăr, 2003). The debris-flow analyzed is located on the eastern slopes of the Červena Hora massif (1337 m a.s.l.; **Fig. 1B**). The massif was originally covered by beech (*Fagus sylvatica*) and mixed forest, gradually giving way to timber-producing spruce (*Picea abies*) forest at higher altitudes. This vegetation has now been replaced by artificially introduced spruce monocultures covering the slopes. The highest parts of the massif reach above the timberline (1,250-1,300 m a.s.l.). The average rainfall in the research area is about 1,500 mm/yr and more than 50 percent of the total precipitation falls during the summer months (Štekl *et al*., 2001). Two high-water periods are typically observed in the rivers in the Sudetes Mountains. The June/July flood, caused by heavy rains, tends to be particularly high (Polách and Gába, 1998). The springtime snow-melt flood is spread over a longer period of time and comes from the thawing of the thick snow cover. The great thickness of snow and relatively steep slopes are determining factors governing the avalanches that sometimes occur on the Červena Hora massif (information from Czech Republic Forestry Services).

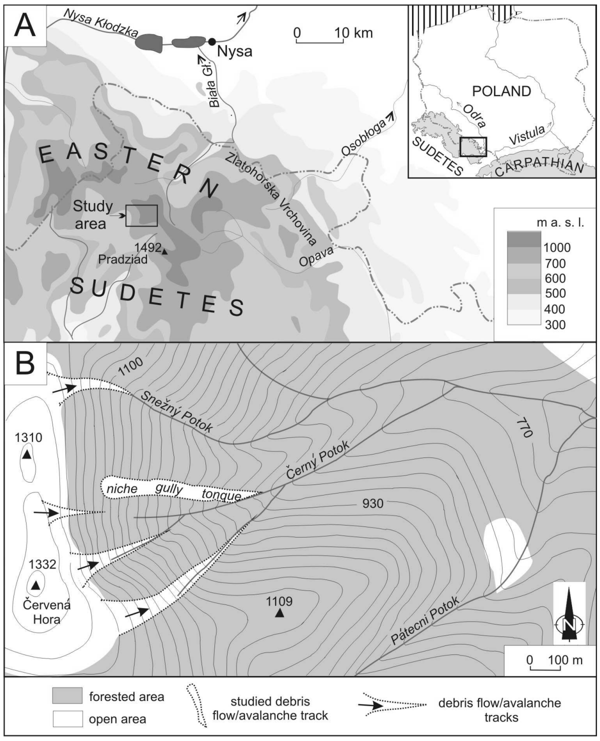

Fig. 1. *Location of the debris flow/avalanche track studied in the Eastern Sudetes mountains (A), on the Červena Hora slope (B).*

Fig. 2. *Debris flow/avalanche track studied on the Červena Hora massif (black arrow).*

Debris flow/avalanche track morphology

The track under study has typical relief for debris flow activity, despite the avalanches that occur on the slope. Therefore in the rest of this paper we have used terms characteristic for debris flow to describe features of the track. The debris flow/avalanche track is located below the timberline on the eastern slope of the Červena Hora massif (**Fig. 1B**). The steep slope gradient and the consequent foliation of mica schists with a thick cover of periglacial slope material are conducive to a repetition of the flow. This part of the Sudetes Mountains is covered by dense forest vegetation. The debris flows and avalanches wound and sometimes break trees thereby also creating suitable conditions for the events that follow. The length of the youngest debris flow/avalanche track is about 750 m. Three distinct sections can be distinguished in its longitudinal profile: the debris flow niche, gully and tongue (**Fig. 1**). The upper part of the debris flow forms a shallow niche with a maximum width of 55 m and a length of about 130 m. Elongated lobes are observed in this part of the landform. The debris flow gully stretches downstream of the niche and forms a distinct erosion trough 4-5 m in depth and 24-35 m wide (**Fig. 3**). The lower section is composed of the debris flow tongue, which fills a 150 m length of the Černy Potok river channel. An accumulation of mineral deposits as well as a large accumulation of logs several meters in thickness have been created in this deposition zone.

Fig. 3. *The gully of the debris flow track/avalanche studied in the Červena Hora massif.*

3. METHODS

Site selection and sampling strategy

An isolated plant island about 20 m in diameter (site 1) is located in the debris flow/avalanche track on the Červena Hora slope. This lies at a distance of 420-510 m above a large accumulation of logs (**Fig. 4**). Beech sprouts growing on the island are wounded during colluvium transport and the scars so produced can give us information about erosion events.

Sites 2, 3, and 4 were located respectively 120-250 m, 2-57 m, and 2-5 m above the large accumulation of logs (**Fig. 4**). The spruce trees sampled were growing on the border between the forest and the debris flow/avalanche track. All of them had scars on the side facing the colluvium transport zone, about 0.5-5 m in height (**Fig. 5**). For tree ring reduction dating we assumed that they produce reduced tree rings after the spruce trees were wounded, so that the age of the scar can be dated. A more precise method for dating spruce wounding is the analysis of the age of the callus tissue bordering the wound and the analysis of tangential rows of traumatic resin ducts within disks collected directly from the edges of the injury. Unfortunately the study area is under protection and we did not get permission from CHKO – Chroniony Krajobrazowy Obszar (Area of Protected Landscape) to collect disks from living trees.

Three sites (5, 6 and 7) were situated in places where there is a large accumulation of logs. Site 5 was located in the marginal zone of a debris flow/avalanche track, between 120 and 240 m above the large accumulation of logs (**Fig. 4**). Sites 6 and 7 were located within the large accumulation of logs in the lower part of the debris flow/avalanche track. Trees fell as a result of colluvium and snow transport and the times of their deaths record the time of the material transport and avalanche events.

Sample collection

Samples consisting of 10 cm lengths of the thickest beech sprouts were collected at site 1. The ages of 8 beech sprouts growing on site 1 and of 6 scars were measured. A core was taken at 0.4 cm above ground level from a single spruce growing on this site. We collected two cores about 1.2 m above ground level along an axis parallel to the slope gradient and from opposite sides of 19 trees at sites 2, 3 and 4.

The authors determined the position of logs in relation to other logs and debris flow sediments at sites 5, 6 and 7, and classified the logs according to whether they lay partially buried under sediment or entirely on it. In the case of logs lying under the sediment, the depth of burial was measured. Discs were taken from 16 logs about 0.3-0.5 m above the root system.

Analyses of material collected

The ages of beech sprouts and spruce collected at sites 1-4 were measured by counting rings under a binocular microscope. Graphs were prepared presenting tree ring width variation in order to determine tree ring suppression within cores collected from spruce sampled along the debris flow/avalanche track. Ring variation from every wounded tree was matched to the chronology which had previously been prepared based on data from local spruce trees (1910-2005; Malik and Owczarek, 2007). Comparison of individual ring curves and the local chronology was necessary because mechanical stress is not the cause of every tree ring reduction (Schwiengruber, 1996). Sometimes climatic factors are responsible for ring reduction and these are clearly recorded in the local chronology and can easily be separated from other types of reduction. The Gleichlaufigkeit (GLK – parallel agreement) test was used for validation (Huber, 1943) both in case of trees and in the case of logs. It was assumed that tree growth reduction occurred when the Tree Growth Reduction Intensity Coefficient (TGRIC) was more than 1.5. TGRIC was introduced by the authors to show the different intensity of reduction recorded in trees. TGRIC is defined as the relation between the mean width of the three following rings from the tree sample being studied and the mean width of the same three following rings from a local chronology (**Fig. 6**). The authors selected three classes of TGRIC:

1) weak reduction, when TGRIC is between 1.5 and 2.
2) moderate reduction, when TGRIC is between 2 and 5.
3) strong reduction, when TGRIC is more than 5.

Taking cores 2 m above ground level reduced the estimated age of trees below the actual age. The age of 15 spruce trees, about 2 m in height, was measured and this showed that spruce need a minimum of 9 years to reach this height. Therefore 9 years were added to the number of years counted within the cores in order to assess the age of spruce more precisely. Where the borehole did not pass exactly centrally through the tree, the size of annual growth increments was interpolated by averaging the sizes of the three oldest rings found within the core. Subsequently, the number of average annual growth increments within the radius of the circle delineated by the oldest annual growth increment included in the core was calculated. Tree ring width curves were constructed from discs collected from logs lying along the debris flow/avalanche track. Tree ring curves were fitted to the local chronology and the death of trees currently lying as logs in the debris flow/avalanche track was dated.

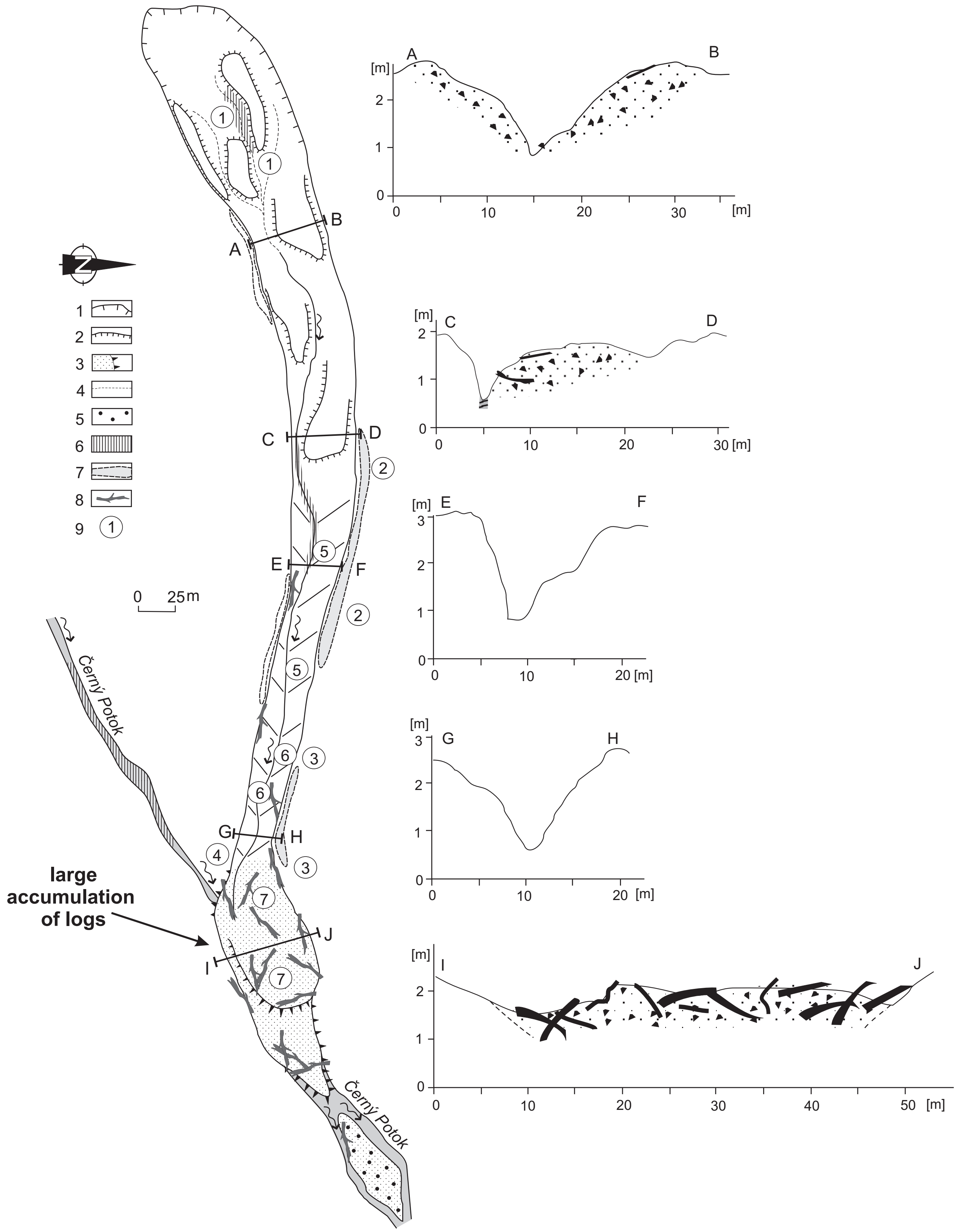

Fig. 4. *Morphological sketch and cross-section of the debris-flow/avalanche track under study. 1 – scar, 2 – edges of accumulation forms, 3 – debris-flow tongue, 4 – periodically drained small gullies, 5 – depositional river channel forms, 6 – bedrock outcrops, 7 – levees, 8 – coarse woody debris, 9 – location of the dendrochronological study sites.*

The authors studied the stage of formation of the last tree ring within logs. We assumed that the tree died during the growing season when the last tree ring had not been entirely produced. In the upper parts of the Jeseniki Mountains the growing season lasts on average from June to August (Šafăr, 2003). When the authors only identified early wood within the tree ring, this meant that the tree had died at an early stage in the growing season. When a tree only produced part of the late wood, the tree had died in the later part of the growing season. Trees had died in the dormant season when the last ring was completely formed. Similar studies were carried out by Perret *et al.* (2006) on samples collected in order to reconstruct rockfall activity in the Swiss Prealps.

4. RESULTS

A detailed map of the track was constructed (**Fig. 4**). All of the trees sampled had started growing in the marginal zones of the debris flow/avalanche track between 1912 and 1963 (**Table 1**). Older trees had colonized the upper part of the track. Clear and numerous tree ring reduction occurred in 1967-68, 1972, and 1975-1977 (**Table 1**). Examples of individual tree ring series from wounded trees growing on the margin of the debris flow/avalanche track are presented in **Fig. 8**. Most cored trees recorded moderate tree ring reduction (**Table 1**). In general, the greatest TGRIC's were recorded in the case of trees growing at sites 3 and 4.

Table 1. *Tree position and their years of ring reduction at sites 2-4 located on the Červena Hora slope.*

site	tree number*	distance above large accumulation of logs [m]	years when trees started growing	years when tree ring reduction started	Tree Ring Reduction Intensity Coefficient (TGRIC)
2	(L) – (B20)	145	1923	1933	2.9
				1942	2.6
				1948	2.3
				1968	2.9
				1975	3.6
				1977	2.9
	(L) – (B21)	175	1912	1922	1.5
				1942	3.2
				1972	3.2
	(L) – (B22)	180	1917	1924	2.7
				1941	3.4
				1975	3.5
	(L) – (B23)	200	1928	1941	3.1
				1952	8.9
				1975	9.2
	(L) – (B25)	250	1952	1973	2.9
3	(L) – (B8)	2	1946	1983	2.2
	(L) – (B9)	14	1950	1997	2.2
	(L) – (B10)	24	1945	-	-
	(L) – (B12)	24	1939	1972	10.6
	(L) – (B13)	34	-	-	-
	(L) – (B14)	42	1942	1972	8.5
	(L) – (B15)	46	1937	1952	3.1
				1967	1.5
				1986	1.5
	(L) – (B17)	46	1941	1967	4.3
	(L) – (B18)	46	1942	-	-
	(L) – (B19)	57	1940	1972	4.9
				1983	2.4
4	(P) – (B1)	4	1963	1998	2.2
	(P) – (B2)	2	1962	1991	2.4
	(P) – (B3)	3	1961	-	-
	(P) – (B4)	5	1960	1976	15.8

***** *(P) – right side of debris flow track; (L) – left side of debris flow track*

Table 2. Position and dating of logs on the Červena Hora slope.

site	log number	distance above large accumulation of logs [m] and location in relation to debris flow track*	position in relation to sediments	assessed year when trees started growing	year of death of trees	part of the growing season when tree was fallen**	gleichlaufigkeit GLK (%)
5	(K20)	(L) – 240	on sediments	1932	1968	EGS	66
	(K19)	(Ś) – 240	on sediments	1920	1968	EGS	71
	(K18)	(Ś) – 210	under sediments – 0.3 m	1958	1994	DS	67
	(K17)	(P) – 170	on sediments	1944	1987	DS	72
	(K15)	(Ś) – 160	on sediments	1956	1991	DS	71
	(K14)	(Ś) – 120	under sediments – 0.3 m-0.7 m	1908	1990	LGS	54
6	(K13)	(P) – 93	under sediments – 0.3 m-0.5 m	1940	1994	DS	62
	(K12)	(L) – 90	on sediments	1937	1994	DS	54
	(K11)	(Ś) – 85	on sediments	1918	1994	DS	60
	(K10)	(L) – 80	on sediments	1909	1991	LGS	48
	(K9)	(L) – 80	under sediments – 0.3 m-0.3 m	1909	1994	DS	74
	(K8)	(L) – 65	under sediments – 0.3 m-0.5 m	1954	1994	DS	69
	(K7)	(P) – 51	on sediments	1952	1997	EGS	65
	(K6)	(Ś) – 41	on sediments	1944	1997	DS	59
	(K5)	(P) – 40	on sediments	1946	1997	EGS	53
7	(K4)	(Ś) – 0	on sediments	1951	1997	EGS	66
	(K3)	(Ś) – 0	on sediments	1949	1985	DS	71
	(K2)	(L) – 0	on sediments	1885	2004	DS	58
	(K1)	(Ś) – 0	on sediments	1958	2004	DS	59

** P – right side, L – left side, Ś – middle*
*** DS – dormant season, EGS – early growing season, LGS – late growing season.*

The date when trees currently lying as logs on the debris flow/avalanche track had started growing lay approximately in the period between 1885 and 1958 (**Table 2**). The trees had died in the period from 1968 to 2004. Groups of trees also fell in 1994 and 1997. Most trees fell during the dormant season, but trees which had died earlier, for example in 1968 and 1997, fell during the first part of the vegetation season. GLK values vary between 48 and 74 (**Table 2**).

5. DISCUSSION

Precision of debris flow and avalanche dendrochronological dating

We can estimate the age of a tree growing on a place where debris flows or avalanches have already occurred. We also can estimate the time which passes between a debris flow or avalanche event and a tree germinating. It should be assumed that at least several or a dozen years must have passed to allow the first trees to germinate. A study carried out in the neighbouring Karkonosze massif has shown that trees can colonize a levee 7 years after a debris flow event (Dunajski, 1998). Finally it seems that the time which passes after a debris flow event and

Fig. 5. *One of the wounded trees growing on the marginal zone of the debris flow/avalanche track.*

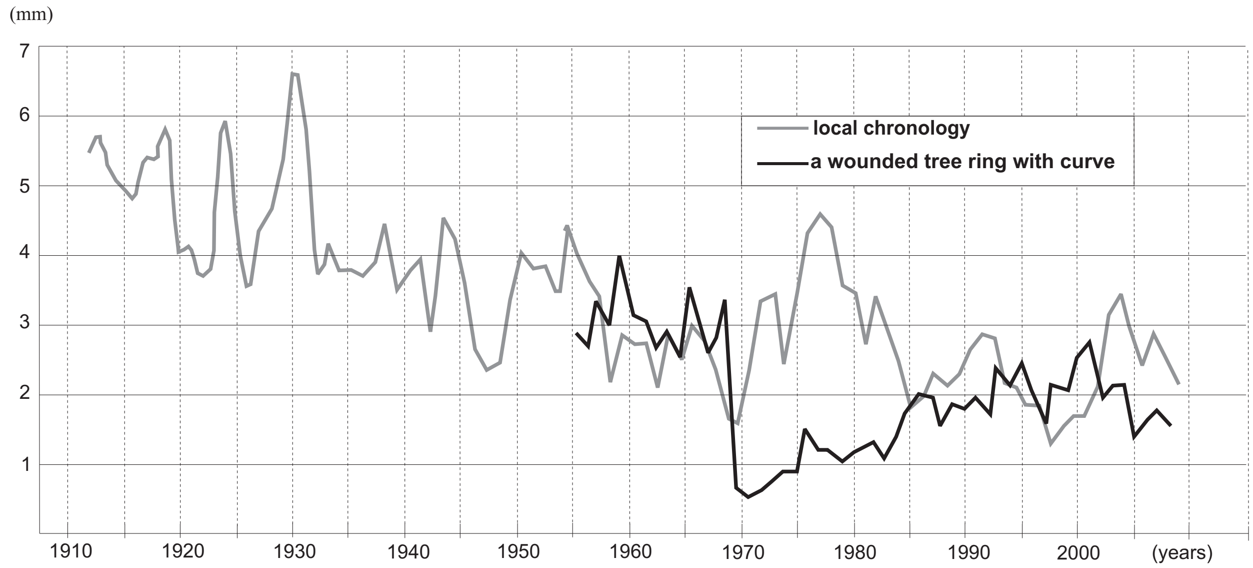

Fig. 6. *One Three following tree rings ("empty" points) within a local chronology and in one of the samples used in the calculation of TGRIC (in this example the mean width of the three following rings from the local chronology = 2.33, the mean width of the three following reduced rings from the wounded tree sample = 0.54, the relation of the mean local chronology tree rings to mean wounded tree sample (TGRIC) = 4.31 (2,33/0,54).*

avalanches is different dependent on the conditions on the site, for example: the degree of rock weathering, slope declination, insolation, water conditions etc. Therefore every attempt to assess the time which had passed between debris flow and avalanches and the first trees germinating could result in an error.

A factor limiting the usefulness of dendrochronological dating of debris flow and avalanches is the age of the trees and sprouts. For example, the age of sprouts on site 1 is from 24 to 58 years, so it is possible to record debris flow and avalanches up to a maximum of 50 years. Trees sampled at other sites are from 42 to 93 years old, which means the authors could only reconstruct the last century of debris flow and avalanche activity on the Červena Hora slope.

A tree often starts to produce a reduced ring a year after a wound occurs, especially when the tree was injured after the growth season. A similar reaction has been observed on riparian alders which had tilted as a result of erosion (Malik, 2006). Wounded trees may even produce reduced rings with a two year delay after the event which caused the reduction. More precise dating of an event which wounded a tree is obtained by the analysis of a half-disk collected with the bordering callus tissue.

It is possible to obtain a wrong tree ring reading within a core taken from a wounded tree. Sometimes it seems that ring reduction is induced by mechanical stress and climatic factors which overlap each other. Such a

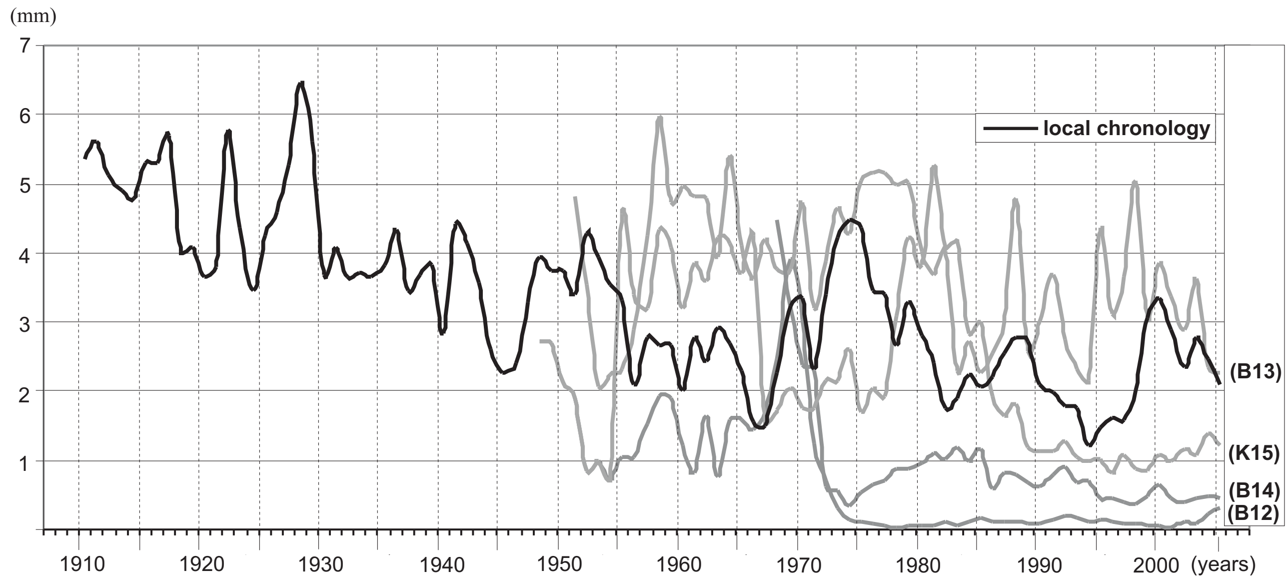

Fig. 7. *Ring width curves of trees from the debris flow/avalanche track studied (trees B12-B15) and the local chronology.*

situation occurred for example in the case of tree (B15) in 1989, so it is difficult to identify the year when the tree reacted to mechanical stress (**Fig. 7**). Log dating is precise when GLK is more than 65%. This occurred in 10 out of the 19 samples analysed, in the case of the other samples GLK was less than 65%. No reduced tree growth data agree with the local chronology but when ring reduction starts, GLK is very low. For example ring width variation of log B14 agrees with the local chronology (GLK is 82%), but since reduction occurred, GLK is very low (36%). Sometimes the last rings are very strongly reduced. This suggests that the tree had been wounded before it died but there are no scars within the tree stem. Perhaps the tree was alive after falling because soil material was still stuck between its roots. This is possible because the authors have observed living fallen trees lying on the slopes of the Eastern Sudetes. Such a situation was observed for log number 10 in which the last four rings of the tree were extremely thin.

Times and conditions of debris flows and avalanches occurring on the Červena Hora slope

The historical record shows that many debris flows on the Červena Hora slopes occurred after the extraordinary rainfall in June 1921 (**Fig. 8**). Precipitation exceeded 200 mm/2 hours (Štekl *et al*., 2001) at the time when the debris flow track studied originated, or at least was widened if it is assumed that it had already been formed before.

The oldest trees grew in the middle part of the debris flow gully, 150-250 m away from the large accumulation of logs. These trees germinated between 1912 and 1932, which means that debris flows or avalanches occurred at the turn of the 19th and 20th centuries, otherwise the trees would be older. Trees growing in some locations on neighbouring slopes are 200 years old.

The separate plant island at site 1 started growing at the end of the 1940s, so we can presume that the debris flows or avalanches which were recorded by dendrochronological data as being created in 1941-42 or earlier included the area of the island. Probably the debris flow which wounded trees at the site had occurred on 19th April 1940 when great rainfall events described by Štekl *et al*. (2001) occurred. On the slopes located above Domaszow (3 km to the southeast of the area studied), the debris flow track was created during a 127.5 mm rainfall event, however we can't exclude the possibility that avalanches occurred at the beginning of the 1940s.

The great majority of the trees and sprouts studied (35 from 46) started growing between 1935 and 1964. All of the trees growing on the left side of the debris flow/avalanche track, and 2-57 m above the large accumulation of logs started growing during that time. It follows that debris flows had occurred on the slope several years before 1935. It is highly probable that an extraordinary debris flow occurred on the slope in 1921. After the debris flow in 1921, trees started to colonize the zone along the margin of the debris track studied.

Two tree ring reductions were recorded in the tree stems growing on the upper and middle parts of the debris flow/avalanche track in 1952 (**Fig. 9**). These must be related to debris flows that occurred on 5th July 1951, because numerous debris flows were observed within the Keprnik massif, 3 km away from the Červena Hora slope, (Polách and Gába, 1998).

Trees sampled on the right side of the debris flow/avalanche track adjoining a large accumulation of logs had started growing between 1960 and 1963. This means that a debris flow or avalanche event must have taken place several or up to a dozen years before, perhaps in 1951, which felled trees on this part of the slope.

Debris flows occurred on the slope studied in 1967-1968, 1971-1973 and 1975-78 (**Fig. 9**) and these can be identified in numerous dendrochronological age determinations. In general, the most frequent debris flows were recorded in 1967-78. This means that slope processes were particularly active at that time. By the mid 1960s trees stopped colonising the zone along the margin of the debris flow/avalanche track, which confirms the great debris flow activity at that time. After the mid 60s trees were very often wounded (**Fig. 9**). The results have shown that the event which occurred in 1967-1968 caused some trees to fall and that the trees had fallen during the early growing season (**Table 2**). This means that trees were felled by debris flow and not by avalanches. The event was additionally demonstrated because 4 tree ring reductions were recorded in 1968 (**Fig. 9**). It is difficult to show which rainfall event was responsible for the debris flow occurring, there is no information in the historical and meteorological sources about any rainfall events at the end of the 1960s. Perhaps regolith transport occurred as a result of a local precipitation event.

The debris flow which followed was induced by a rainfall event which occurred on 29th May 1971 (**Fig. 9**). In total 120-160 mm of precipitation fell in the Eastern Sudetes mountains area, and numerous debris flows occurred on many slopes (Gába, 1992; Štekl *et al*., 2001). In 1971 two beech sprouts were wounded and four major tree ring reductions were recorded within spruce stems in 1972 (**Fig. 9**). It seems that the 100-120 mm/day precipitation which occurred on 20th August 1972 induced the next debris flow. The next time a tree ring reduction was recorded was in 1975-1977, and we cannot exclude the possibility that the rainfall occurring on 31st July 1977 caused a reaction in the trees (Štekl *et al*., 2001). Four trees lying as logs on the track only produced early wood in 1997. This means that debris flow occurred on the slope in 1997. The debris flow occurred as a result of great precipitation occurring in the Eastern Sudetes over the period 6th-9th July 1997. Regolith was redeposited on numerous slopes and valleys during this event (Zieliński, 2003).

Younger regolith transport events confirmed by dendrochronological dating could be the result of snow-induced debris flows or avalanches. Four logs felled in 1994 and one felled in 1991 were buried by sediments up to 0.7 m in depth. Simultaneously most of the trees felled in the 1980s and 1990s have produced an entire last tree ring, despite the fact that lots of debris flows occurred on neighbouring slopes in 1991. This means that the logs fell outside the growing season, most probably as an effect of avalanches or snow melt which was connected with regolith transport.

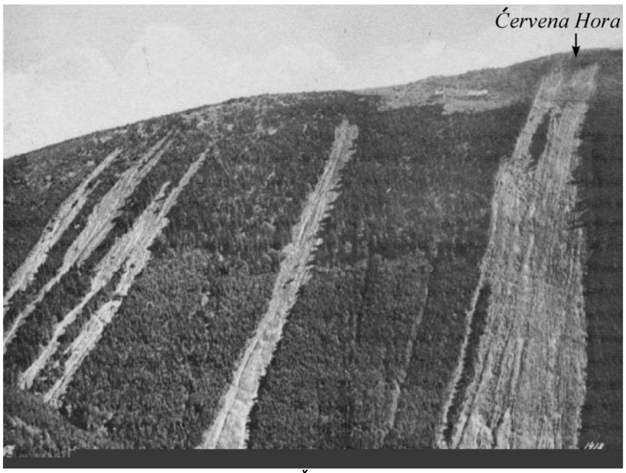

Fig. 8. *Debris flow tracks in the Červena Hora massif after the intensive precipitation event in June 1921.*

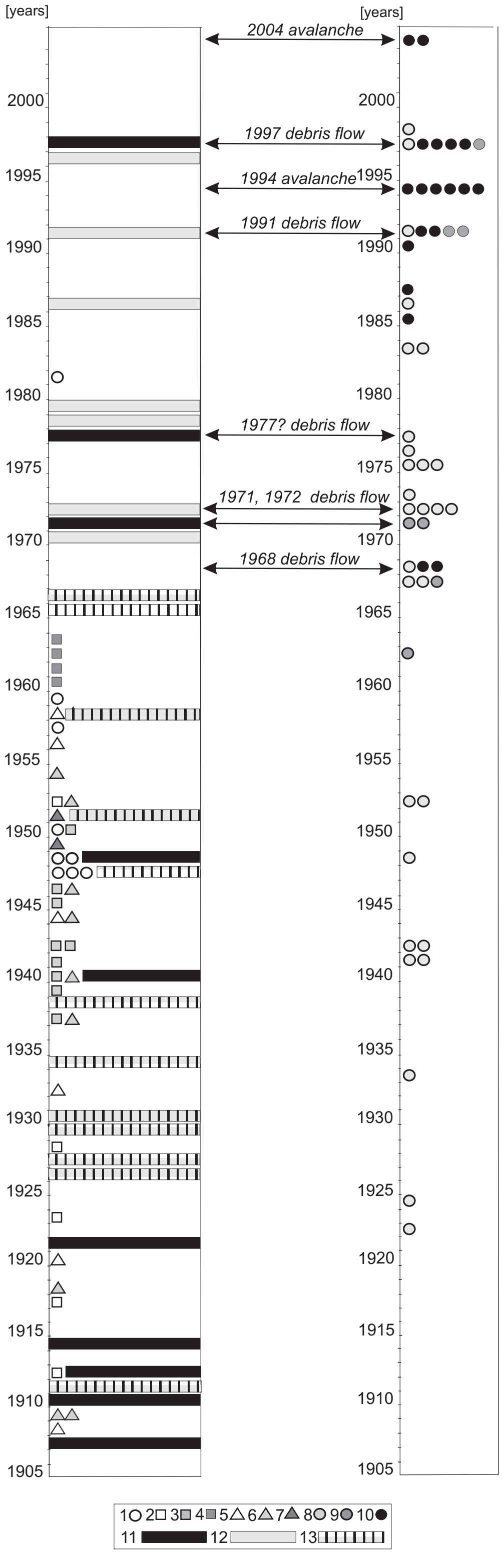

Fig. 9. *The results of dendrochronological dating of debris flows and avalanche activity on the Červena Hora slope and the main precipitation and flood events that occurred in the Eastern Sudetes mountains. 1 – age of beech sprouts (site 1), 2 – age of trees (site 2), 3 – age of trees (site 3), 4 – age of trees (site 4), 5 – age of trees/logs (site 5), 6 – age of trees/logs (site 6), 7 – age of trees/logs (site 7), 8 – tree ring reductions (sites 1-7), 9 – scars on beech sprouts (site 1), 10 – age of logs (sites 5-7), 11 – rainfall events: more than 100 mm/day recorded in Eastern Sudetes (Štekl, 2001), 12 – rainfall events between 20 and 100 mm/day recorded in the Eastern Sudetes (Štekl, 2001), 13 – relatively small rainfall/flood events recorded in the Eastern Sudetes (Polách and Gába, 1998).*

The oldest logs fell in 1968, others fell in 1991, 1994 and 1997 (**Fig. 9**). When we come down slope the logs get younger and younger. This means that when logs fall, most of them reach the great accumulation of logs, where recumbent logs record debris flows and/or avalanche events. During the transport, part of the log mass is thrown aside onto marginal parts of the debris flow/avalanche track. They did not always get transported in the following debris flows or avalanches, therefore relatively old logs lie in the upper part of the slope.

Debris flow and avalanche activity in the Eastern Sudetes

Numerous mineral material and snow transport corridors function within completely forested slopes in the Eastern Sudetes mountains. Corridors occurred in the closed forest as a result of debris flow events, because it is not possible for avalanches to form on forested slopes. Regolith is only removed from the axis of the debris flow track and levees are formed on the margins of the track. When a corridor is opened on a slope, avalanches can occur. They widen a corridor because trees are cleared from the margins of a track. Similar corridors where avalanches and debris flow occur together were described by Butler (2001). When the regolith located in the margin of track is exposed from beneath trees, it is prone to transport so mineral material is transported as debris flow, or by avalanches during appropriate meteorological conditions, and the corridor is widened. Sometimes when debris flow or avalanches are not occurring on a corridor, trees colonize the margins of tracks. The presence of regolith on the marginal zone of the track allows fast tree growth (sometimes less than decades). It is difficult to say if it is possible to completely close the corridor. If we take the presence of bedrock in the middle part of the corridor into consideration, the closing of the corridor is probably only possible in the long term when weathering forms new regolith and soil. It would appear more likely that the corridor is open all the time and material is systematically transported, so that after a long time the corridors are transformed into valleys which cross the mountain massif.

6. CONCLUSIONS

The debris flow/avalanche track studied was formed or most probably widened in 1921 during an extraordinary rainfall event. After the event, trees gradually colonized the margins of the debris flow track until 1968 when the first debris flow was strongly recorded in the tree rings. Since that time debris flows have proved very common (1968, 1971-1972, 1977?, 1991, 1997). Material transport events which occurred in 1994 and 2004 were induced by avalanches or snow melt debris flow. In favourable geological conditions regolith could even be transported in closely forested slopes of the mid-mountain zone. Regolith transport corridors function periodically on the slopes during periods of great precipitation frequency and intensity.

Avalanche and/or snow melt debris flow can occur in the corridors. During debris flow events and avalanches trees are cleared from the margins of debris and corridors are widened.

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