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DENDROCHRONOLOGICAL METHODS FOR RECONSTRUCTING MASS MOVEMENTS – AN EXAMPLE OF LANDSLIDE ACTIVITY ANALYSIS USING TREE-RING ECCENTRICITY

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Abstract: Dendrochronological methods can be applied to the reconstruction of different types of environmental events such as climate changes, fires, glacier movements, floods, earthquakes, volcano activity. In the field of geomorphology dendrochronology is increasingly frequently used for the absolute dating of different types of mass-movements (rock falls, landslides and debris flows, etc.). Trees growing on slopes transformed by mass-movements are tilted and wounded while their stems and root systems are exposed or buried under sediment. These events are recorded in wood anatomy as eccentric growth, reaction wood, scar overgrowth by callous tissue, changes in cell size or adventitious root production. Dating changes in wood anatomy allows to date and precisely reconstruct the spatial and temporal occurrence of mass-movements with at least one year resolution. The paper provides a review of existing dendrochronological tools used in geomorphology and also an example of the application of eccentric tree-growth to reconstruct landsliding. Using tree-ring eccentricity allows to (1) obtain a dynamic depiction of slopes, (2) study landslide activity, not only contemporary, but also in the last tens of hundreds of years (depending on the stand age).

Keywords: dendrochronology, mass movement, landslide, eccentricity of tree rings, Sudetes.

1. INTRODUCTION – TREE RING FORMATION AND THEIR POTENTIAL ROLE IN ENVIRONMENTAL RECONSTRUCTIONS

Trees produce rings which are formed as a result of periodic growth. The way in which trees grow in width is to add a layer of new wood cells between the older wood and the bark over the whole perimeter of the stem. The cambium, meristematic tissue consisting of cells that divide rapidly to form new layers of tissue (Kaennel and Schweingruber, 1995), is responsible for this growth. Over the whole growth season the layers of cells create a ring. The tree stem, both branches and roots, grows in diameter as the ring is added.

Trees growing in an area with seasonality in temperature and/or precipitation, especially those growing in temperate climates (between the tropics and the polar circles), produce clear seasonal rings. In North America, and Western and Central Europe, where studies on tree rings started and have been developed, trees produce annual rings from spring to autumn during the growing season. After the dormant season, in spring, trees produce large cells (coniferous) or vessels (broadleaves) as water is abundant and growing conditions are generally good. At the end of summer when the season becomes drier and comes to a close, trees produce smaller cells that have thicker walls. In the late autumn, the growth stops. The following spring the next layer of large cells is formed and can be easily distinguished from the small cells pro-

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duced at the end of previous growth season; the borderline between rings is distinctive. In the case of coniferous trees every annual ring which represents each year of growth, is composed of a light band of wood (growth in spring/early summer) and a dark band (late growth in summer/autumn). In the case of broadleaf trees the first part of the annual ring is, in most cases, composed of large vessels visible even to the naked eye. The second part is composed of relatively small, invisible vessels.

Clear border between rings allows one to calculate the age of the tree. The width of every annual ring reflects the ontogenetic properties of a certain tree and the conditions in the surrounding environment in a certain growing season. When environmental stress appears during growth, trees tend to develop narrower rings, e.g. most tree species produce very thin rings during years of drought and large rings during the years of wet conditions (Baas, 1982; Carlquist, 1988; Schweingruber *et al.,* 2006).

Due to their growth patterns, trees can record various types of environmental events in their rings (Fritts and Swetman, 1986). As a result several branches of dendroecology have developed (Schweingruber, 1996; Zielski and Krąpiec, 2004):

- dendroclimatology – uses tree-ring dating to reconstruct and make studies on past and present climates,
- dendrogeomorphology – uses tree-ring dating for studies on geomorphic processes such as: river erosion and accumulation (e.g. Gärtner *et al.,* 2001; Malik, 2006), dune migration (e.g. Koprowski *et al.,* 2010) mass movements (e.g. Perret *et al.,* 2006; Malik and Owczarek, 2009; Migoń *et al.,* 2010), etc.,
- dendropyrology – uses tree-ring dating for studies of the history of fires,
- dendroglaciology – uses tree-ring dating for studies on the movement of glaciers,
- dendrohydrology – uses tree-ring dating for studies on water phenomena,
- studies on tectonic and volcanic activity via their impact on tree ring development,
- studies on forest stand dynamics and on the changes in the structure (health, age structure) of forest communities through time,
- analysis of anthropogenic impacts on the environment, such as air pollution, through studies on tree ring development.

The aim of the study presented in the paper is to provide a review of existing basic dendrochronological tools used in geomorphology and also to present an example of the application of eccentric tree-growth to reconstruct landsliding. Eccentric tree rings develop as a direct result of mechanical stress and the impact of gravity on tree stems. These are not widely used in dendrogeomorphology in contrast to reaction wood. Existing methods of eccentricity analysis are not well suited to the needs and requirements of geomorphology. The aim of the paper is to present the potential of this tool for the reconstruction of landsliding events using the Keprnický landslide in the Eastern Sudetes, Czech Republic as an example. The paper presenting a review in tools of dendrogeomorphology used in studies of active slopes and providing an example of application of tree-ring eccentricity in landslide studies is directed not only to geomorphologists, but also to experts in e.g. hydrology, geoengineering, forestry etc.

2. TYPES OF MASS MOVEMENTS AND THEIR IMPACT ON HUMAN LIVES

A mass movement is the downward and outward movement of slope-forming material under the influence of gravity (Dikau, 2004). The main types of mass movements are:

- lateral spreading – the lateral extension of a cohesive rock or soil mass over a deforming mass of softer underlying material (**Fig. 1A**),
- toppling – the forward rotation of a mass of rock, debris or soil about a pivot or hinge (**Fig. 1B**),
- rock fall – a free movement of material from steep slopes (**Fig. 1C**),
- landslide – a movement of material along a recognizable shear surface (**Fig. 1D**).
- debris flow and soil flow – a landslide in which the individual particles travel separately within a moving mass usually saturated with water (**Fig. 1E**).

Mass movements can have a catastrophic effect – events such as landslides, rockslides, and rock avalanches can be large-scale and rapid. They can be triggered by volcano eruptions, earthquakes or simply by long-term and/or heavy precipitation events. One of the most catastrophic episodes of mass movement was associated with the eruption of Mount St. Helens in 1980. Magma movement produced a bulge on the north side of the volcano that then failed producing three large landslides. The

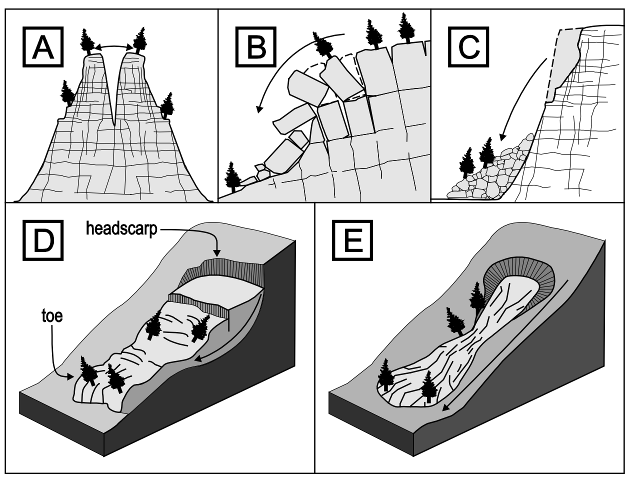

Fig. 1. *Types of mass-movements with the location of trees affected (possibly recording the geomorphic impact): A – lateral spreading, B – toppling, C – rock fall, D –landslide, E – debris flow.*

volume of the material removed by landslides was estimated to about 2.3 km^3 (Yamaguchi, 1985). In 1959, an earthquake triggered a catastrophic landslide that dammed the Madison River in Montana and created Earthquake Lake (Christopherson and Averill, 2007). Mining operations triggered rock avalanches, that buried the towns of Frank in Alberta in 1903 and Elm in Switzerland in 1881 (Buss and Heim, 1881). There are also many examples of less spectacular mass movements that destroyed infrastructure, mainly buildings such as houses.

3. TREE-RING ANALYSES AS A TOOL FOR MASS MOVEMENT STUDIES

Basic information

Tree ring analyses have made considerable contributions to mass-movement studies (e.g. Alestalo, 1971; Shroder, 1980; Butler, 1987; Wiles *et al.,* 1996; Lang *et al.*, 1999; Solomina, 2002). Trees growing in climates with distinct seasonality preserve evidence of past mass-movement with annual and sometimes even monthly resolution. Tree-ring records may represent one of the most precise natural archives for reconstructing, and therefore understanding, past mass-movement events. Most dendrochronological studies concentrate on the reconstruction of the spatial and temporal distribution of different types of mass movements such as rock falls (Stoffel *et al.,* 2005; Stoffel and Perret, 2006; Perret *et al.,* 2006), landslides (Shroder, 1978; Begin and Filion, 1988; Jacoby *et al.,* 1992; Fantucci and Sorriso-Valvo, 1999; Gers *et al.,* 2001; Stefanini, 2004; Migoń *et al.,* 2010), debris flows (Baumann and Kaiser, 1999; Bollschweiler *et al.,* 2007; Bollschweiler *et al.,* 2008; Stoffel *et al.,* 2008; Malik and Owczarek, 2009; Zielonka and Dubaj, 2009; Arbellay *et al.,* 2010) and others (Denneler and Schweingruber, 1993).

Dendroecological studies always start by taking samples from trees growing in the area, where we expect the processes/events being studied to occur or have an effect (basin on e.g. earlier geomorphic mapping). In the case of mass movement studies we select a slope where landforms recording past events occur (e.g. on landslide slopes: headscarps in the upper part and toes in the lower part) (**Fig. 1D**). The second step is to select trees from the population growing on the landslide slope, if possible growing at a similar distance from each other, distributed regularly on the surface studied. For the sampling we select trees visibly influenced (deformed) by mass-movements – with tilted or wounded stems, roots or stems exposed or buried under sediment (**Fig. 2**). Non-geomorphic factors can cause disturbances similar to the geomorphic ones, e.g. trees can also be wounded by neighbouring trees falling down, rather than by debris flow, they can be tilted by wind rather than landsliding. Therefore, the selection of trees that mainly record the effects of mass-movements is important to reduce the probability of receiving data disturbed by other environmental factors.

Pressler borers are used to extract samples (cores) from tree trunks or, sometimes, discs are taken from stems and roots using saws. Cores and disks are polished with sand paper to reveal ring structure. The next step is to count and measure tree rings with the use of electronic measuring systems. This operation gives us data of one-year precision and the calendar dates of ring formation are obtained. Finally, we obtain curves of tree-ring width for individual trees. To be sure that the tree-ring curves obtained record mass movement events, they have to be compared with ring series from trees growing on a reference (control) slope. The reference slope should be located as close as possible to the landslide slope studied. The inclination, orientation and bedrock of the reference slope should be similar to the one being studied. The morphol-

Fig. 2. *Tree reaction to mass-movement events: A – trees tilted upslope on a landslide, B – stem wounded by debris flow, C – tree roots exposed by landsliding (marked with arrows), D – tree stem buried by debris flow sediment (marked with arrows).*

ogy of the reference slope should not show signs of past or present mass-movement activity. By meeting these requirements we assume that the trees growing on the reference slope mainly produce tree rings under the influence of non-geomorphic factors, and the influence of mass movement on tree ring width is minimal. The sampling procedures should be the same for the main (landslide) and the reference slopes. Ring series from trees growing on the main and reference slope should be overlapped and compared to distinguish ring width disturbances affected by mass-movements.

Dendroecological studies generally bring some problems connected with the process of tree-ring formation. The main problems in dating ecological events (climatic, geomorphic, etc.) arise from missing and false rings. Missing rings are formed when cell production in a certain growing season is completely stopped on the whole perimeter or present only on part of the stem (formation of a wedging ring). When sampling a tree with a missing ring(s) we get incomplete time series. False rings are the effects of the fluctuation in wood density within one tree ring and are visible as dark shadows parallel to ring boundaries (Stokes and Smiley, 1968), which imitate normal latewood. Instead of one annual ring we find two narrower ones. Skeleton plot procedures are the best method to eliminate mistakes connected with the presence of missing or false rings (Schweingruber, 1988; Cook and Kairiukstis, 1990). Skeleton plotting allows to date tree rings on the basis of visual assessment of relative ring widths. This approach allows one to identify pointer years (narrower – negative and wider – positive) formed as an effect of major ecological events.

Wood anatomy features, other than tree-ring width, are sometimes more precise tools for recording mass-movements. Wood micro sections prepared from wounded trees enable the dating of scars with intra-annual precision. Root exposure can be dated using changes in the size of cells and the formation of latewood (**Fig. 3D**) which can be observed on micro sections prepared with the use of microtomes. Microtomes allow wood slides as thin as about 10–20 μm to be cut. Subsequently, wood samples can then be analysed with a binocular microscope to search for features of the wood anatomy indicating the occurrence of mass movements (Gärtner *et al.*, 2001; Gärtner, 2007).

Tree-rings in mass movement analyses

The types of mass movements that wound trees are mainly rock falls and debris flows (**Fig. 2B**). After a wounding episode the tree gradually heals the trunk/root and closes the wound by growing soft callus tissue. Obtaining disc samples from wounded trees allows one to precisely date the scars. Dating mass-movements with the use of scarred trees is done by counting the tree rings formed after wounding (**Fig. 3C**). Using cores for scar dating is more problematic, so a wedge cut through the overgrowing callus is recommended (Baumann and Kaiser, 1999; Bollschweiler *et al.,* 2007; Arbellay, 2010).

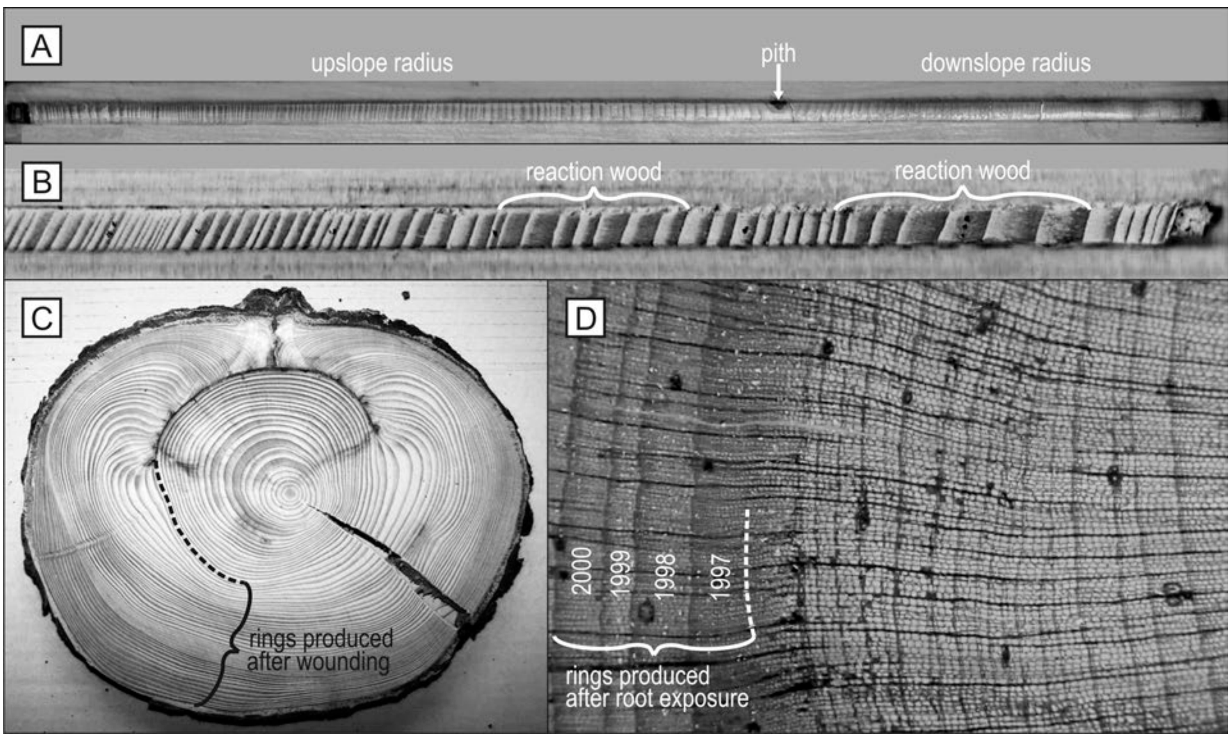

Fig. 3. *Wood anatomy features formed by the influence of mass-movement events: A – eccentric growth pattern in a coniferous tree (Norway spruce) tilted upslope, B – reaction wood, C – scar and rings formed after wounding, D – cell diameter decrease and formation of latewood after root exposure.*

Trees can be uprooted by slope deformations caused by landslides. Roots can also be exposed by debris flow eroding and transporting material in forest zones (**Fig. 2C**). After a mass-movement event which has exposed tree roots from the soil cover, the cells in roots became more numerous and smaller than before exposure (diameter decrease of about 50% in early wood, **Fig. 3D**). Also, the late wood become more distinct. The counting of the number of tree rings produced after exposure allows dating mass-movement events (Carrara and Carroll, 1979; Gärtner *et al.,* 2001; Vandekerckhove *et al.,* 2001; Bodoque *et al.,* 2005; Gärtner, 2007; Hitz *et al.,* 2008, Malik, 2008; Malik and Matyja, 2008).

Tree stems can be buried with sediment from debris flows and, less frequently, by material from landslide toes. After a burying event trees abandon deeply covered root systems and produce adventitious roots in fresh sediment (**Fig. 3D**). Calculation of the ages of adventitious roots enables to date the minimum age of mass-movement events. Such roots can be produced up to 7 years after the event (Strunk, 1989; 1997). The age of adventitious roots can be calculated by the sampling of wedges collected from the stem in the place where the root was produced and by then counting the rings formed after the root initiation.

Trees growing on unstable slopes tend to be tilted and as a result they have tilted (**Fig. 2A**) and deformed stems. They can be tilted/bent under the influence of various types of mass movement (e.g. lateral spreading, landsliding, debris flow) (**Fig. 1**). The character of the deformation produced depends on the direction of tilting: upslope or downslope.

The Norway spruce (Picea abies Karst.) analysed in the case study from the Keprnický site are bent in the direction of the valley axes when tilted downslope and can have straight, s-shaped or "pistol-butted" stems. Spruce trees tilted upslope usually have straight or "pistol-butted" stems bent in the upslope direction. It was observed, that spruce growing on landslide slopes also have deformed stem cross-sections: oval, elongated parallel to the slope inclination. Spruce trees growing on stable slopes, without visible signs of mass movement, have straight vertical stems. They do not have significant deformations of the stem cross-section. (**Fig. 4**)

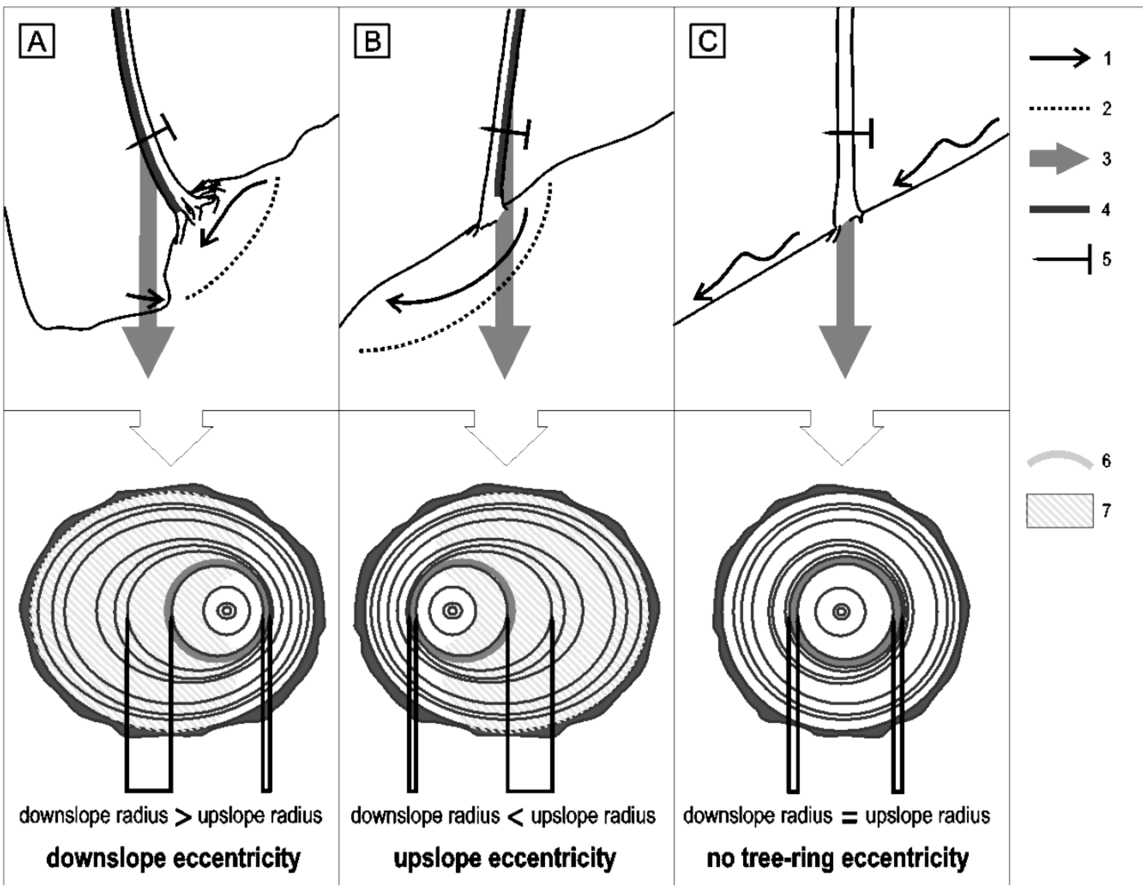

Fig. 4. *Development of: A – downslope eccentricity of tree rings in tree tilted downslope, B –upslope eccentricity of tree rings in tree tilted upslope, C – lack of eccentricity in straight tree stem (example of Picea abies Karst.). 1 – direction of impact of geomorphic processes, 2 – sliding surfaces, 3 – gravity force, 4 – part of the stem developing wider rings and reaction wood, 5 – stem cross-sections, 6 – ideally concentric ring, 7 – zone of reaction wood development.*

External deformations of stems, connected with slope instability, affect the anatomical structure of the wood produced. Trees produce reaction wood and an eccentric growth pattern when influenced by mechanical stress and by gravity. We distinguish two types of reaction wood, compression wood – produced by coniferous trees and tension wood – formed by deciduous trees. Compression wood is dense and hard, visible as a dark brown ring composed of thick-walled cells (**Fig. 3B;** Schwiengruber *et al.,* 2006). Tension wood is more difficult to recognize; it is composed of fibrous cells that contain thickened walls, have higher density than normal fibres and are shrunk and swollen longitudinally.

Eccentric growth develops when a tree produces wider rings on one side of the stem and narrower rings on the other. The pith is displaced as a result of this (**Fig. 3A**). Taking samples from trees growing on landslide slopes has revealed that the pith does not coincide with the geometric centre of the stem cross-section (**Fig. 3A**, **Fig. 4A-B**) – tree rings are eccentric. Eccentricity can be distinguished on ring width graphs of single trees (**Fig. 5**) as the separation of the upslope and downslope curves over the long-term. Such graphs show that tree ring width on one side of the stem increases or decreases abruptly in comparison to the opposite side.

Coniferous trees (among them: Norway spruce), produce wider rings on the lower (bottom) part of the stem, that is: the upslope part of the stem when bent upslope (**Fig. 4B**) and the downslope part of the stem when bent downslope (**Fig. 4A**). Wider rings are accompanied by compression wood. Among deciduous trees the tendency of eccentricity is the opposite: wider rings are produced on the upper (top) parts of stems and are accompanied by tension wood. The first tree ring (the oldest one) showing eccentricity or reaction wood provides information on when the tree had started to react to the impact of the mass-movement (Braam *et al.,* 1987a; 1987b). Distinguishing the end of the event is more difficult, because the formation of reaction wood and eccentric growth can continue for an unknown number of years after the mass movement event. Similar results for eccentricity in coniferous trees, as in Sudetes, were obtained by: Schweingruber (1996) – for spruce, Stokes and Berthier (2000) – for Pinus pinaster Ait., Krąpiec and Margielewski (2000) – for spruce and fir.

Anatomical disturbances caused by tree tilting are most distinct in the axis parallel to the deforming force (mass movement). An important element of the sampling strategy, when studying tilted/bent trees, is to extract cores parallel to the direction of stem tilting and to try to reach a tree centre (pith).

Above described features of wood anatomy do not occur only as a consequence of geomorphic impact. Numerous other factors can cause disturbances of tree growth. Trees can injure their neighbours when falling down, stems can be also injured by ice floe flowing down the rivers (Zielonka *et al.*, 2008). Winds bending the stem or asymmetric growth of the crown can cause development of reaction wood and eccentric tree rings (Zielonka and Malcher, 2009). Thus it is always necessary to take into consideration the possibility of the occurrence of a non-geomorphic factor causing growth disturbances recorded in the wood anatomy of trees.

4. ECCENTRICITY OF TREE RINGS – A TOOL FOR SPATIAL AND TEMPORAL ANALYSES OF LANDSLIDES

Until now, it was mainly the presence of reaction wood that has been used to date landslides in dendrogeomorphic analyses. At the same time the eccentricity of tree rings was often neglected. This happened despite the fact that eccentricity is directly related to trunk deformations under the mechanical stress involved and under the force of the Earth's gravity. In the past little dendrochronological research was done on relations between the development of eccentricity, the development of reaction wood and the presence of stresses and deformations of tree trunks (Schweingruber, 1996). Single analyses of coniferous species were made for the needs of forestry (Mäkinen, 1998; Stokes and Berthier, 2000), anatomical studies, climatology (Schweingruber, 1996) and within studies on the adaptation of trees to environmental conditions – e.g. wind (Wade and Wendel-Hewson, 1979).

The possibility of using tree-ring eccentricity in geomorphology was noticed by Hupp (1986), Malik and Ciszewski (2008) for fluvial erosion, by Vanderkerckhove *et al.* (2001) for gully erosion and by Koprowski *et al.* (2010) for the migration of coastal dunes. The phenomenon of tree trunk tilting on active slopes and their bending under the impact of gravitational mass movements such as creeping and sliding, was observed by Parizek and Woodruff (1957), Braam *et al.* (1987a; 1987b) and Schweingruber (1996).

The most accurate description of the pattern of tree tilting under the impact of mass-movement (mud flows) was given by Braam *et al.* (1987a; 1987b). These authors have also proposed a formula for the calculation and analysis of eccentricity. An attempt to systematise the use of eccentricity was also made by Casteller *et al.* (2008) in studies on snow avalanches. These authors have used an eccentricity index, developed by Schweingruber (1996) for studies of snow creep and have also proposed an original indicator which has been prepared for reconstructions of snow avalanche activity. Another method of calculating the index was employed by Burkhalter during studies on tree adaptation to wind (Schweingruber, 1996).

None of the formulae used for calculating eccentricity mentioned above can be efficiently and successfully employed for dendrogeomorphic studies of landslides. They do not allow to distinguish the direction of tilting and eccentricity (upslope from downslope) (**Fig. 4**). They do not allow to compare the upslope and the downslope eccentricity values. They lack accurate tools for distin-

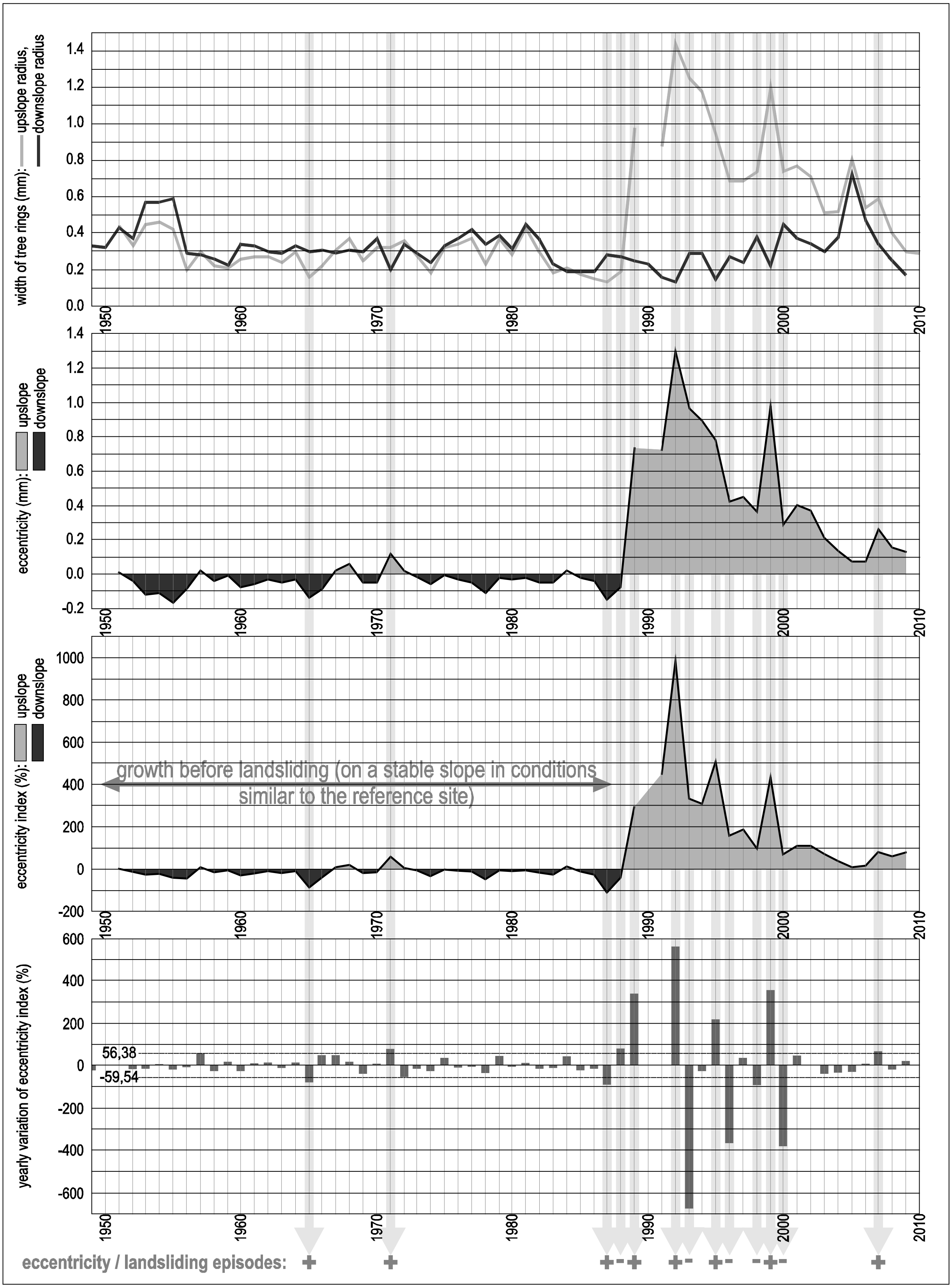

Fig. 5. *An example of a tree-ring series transformation from ring widths into eccentricity, eccentricity index and its yearly variation, with eccentricity episodes dated on the basis of thresholds from the reference site (56,38% and -59,54%).*

guishing sliding events from the eccentricity record. The eccentricity record is implicit – the same record is given for different types of events. The methods contain elaborate, complicated statistical procedures – not adjusted to the needs of geomorphology; a flexibility of statistical approach also results in a poor universality of the methods. These methods lack comparison with the results from reference sites located on stable slopes.

Calculation of the eccentricity index

In order to avoid the disadvantages mentioned above, in the studies conducted at the Keprnický site, tree-ring widths measured on both sides of the trunks (downslope: D (mm), upslope: U (mm)) were recalculated into eccentricity (E (mm)) and eccentricity index (Ei (%)) with the use of the newly developed formulae:

$$Ex\ (mm) = Ux - Dx; \tag{4.1}$$

when Ex (mm) > 0: upslope eccentricity;

$$Eix\ (\%) = (Ex / Dx) \times 100\% > 0; \tag{4.2a}$$

when Ex (mm) = 0: lack of eccentricity;

$$Eix\ (\%) = Ex\ (mm) = 0; \tag{4.2b}$$

when Ex (mm) < 0: downslope eccentricity;

$$Eix\ (\%) = (Ex / Ux) \times 100\% < 0; \tag{4.2c}$$

where:
U – width of tree ring in the upslope part of the trunk (mm); D – width of tree ring in the downslope part of the trunk (mm); E – eccentricity of tree ring (mm); Ei – eccentricity index of tree ring (%); x – year (annual tree ring).

The difference between the tree-ring widths on the upslope and the downslope part of the trunk is examined in relation to the narrower of these two radii. The narrower radius is considered as 100% or -100% (respectively: upslope and downslope eccentricity). The wider radius can be described as the sum of the narrower one plus the value of upslope/downslope eccentricity index (respectively: 100% + Ei (%) i -100% + Ei (%)).

Eccentricity indicators (in mm and percent) should be calculated for each annual ring in the samples taken. The values obtained for each tree and year can be presented on graphs (example of transformations from ring widths into eccentricity index – sample from the Keprnický study site: **Fig. 5**).

Landslide dating using the eccentricity index

The moments of slope movement are recorded on the eccentricity index graphs of single samples as abrupt, year after year, changes of the course of the curve:

- among upslope eccentricity – an abrupt increase in the index value (from positive/negative to positive) (**Fig. 5**: 1971, 1989, 1992, 1995, 1999, 2007),
- among downslope eccentricity – an abrupt decrease in the index value (from positive/negative to negative) (**Fig. 5**: 1965, 1987).

Cases of year after year decreases of index values within positive value range or increases within negative value range, were interpreted as tree recovering, and returning into balance after periods of destabilization by the mass movements (**Fig. 5**: 1988, 1993, 1996, 1998, 2000).

The relative yearly change of the index value was used to date the landslide. To facilitate the dating of landslide events, the yearly variation of eccentricity index was calculated (vEix (%)), as the difference between the index value for a certain year and for the year before:

$$vEix\ (\%) = Eix - Eix\text{-}1; \tag{4.3}$$

where:
Ei – eccentricity index of tree ring (%); vEi – yearly variation of eccentricity index (%); x – year (annual tree ring).

The formula applied allows one to spot relative changes in the index values. Bar graphs of the yearly variation of the index were created for individual samples (**Fig. 5**). Variability graphs can be interpreted visually or landsliding events can be marked objectively – based on the results obtained for reference slopes. For each study site the results from a matching reference slope nearby should be used – the values of yearly variation for all years, for all reference samples should be considered. Arithmetical means and standard deviations are calculated separately for the set of increases (yearly variation vEi > 0), and decreases (vEi < 0). The values of means plus deviations are used as thresholds for determining the most distinct, abrupt changes of eccentricity index value at the study sites. After considering the directions of changes (only increases into positive values and decreases into negative values can be included), these thresholds can be used for dating the most probable moments when landslides were activated on the slopes studied (**Fig. 5**).

5. LANDSLIDE ACTIVITY ON A SLOPE OF THE KEPRNICKÝ VALLEY (EASTERN SUDETES, CZECH REPUBLIC, CENTRAL EUROPE) – AN EXAMPLE OF APPLICATION OF THE ECCENTRICITY INDEX

The location of the study site

The studies were conducted in the mid-mountain range of the Hrubý Jeseník in the Eastern Sudetes, Czech Republic (**Fig. 6**). The valley of the Keprnický stream is located in the Keprník-Šerák massif (1423-1351 m a.s.l.) where the bedrock is composed of metamorphic rocks (schists and gneisses within the study site). The average total yearly precipitation in the area of the study was 921.1-1025.0 mm for the period 1961-2000.

The study site is located in the middle section of the Keprnický valley (**Fig. 6**) on a slope with landslide relief

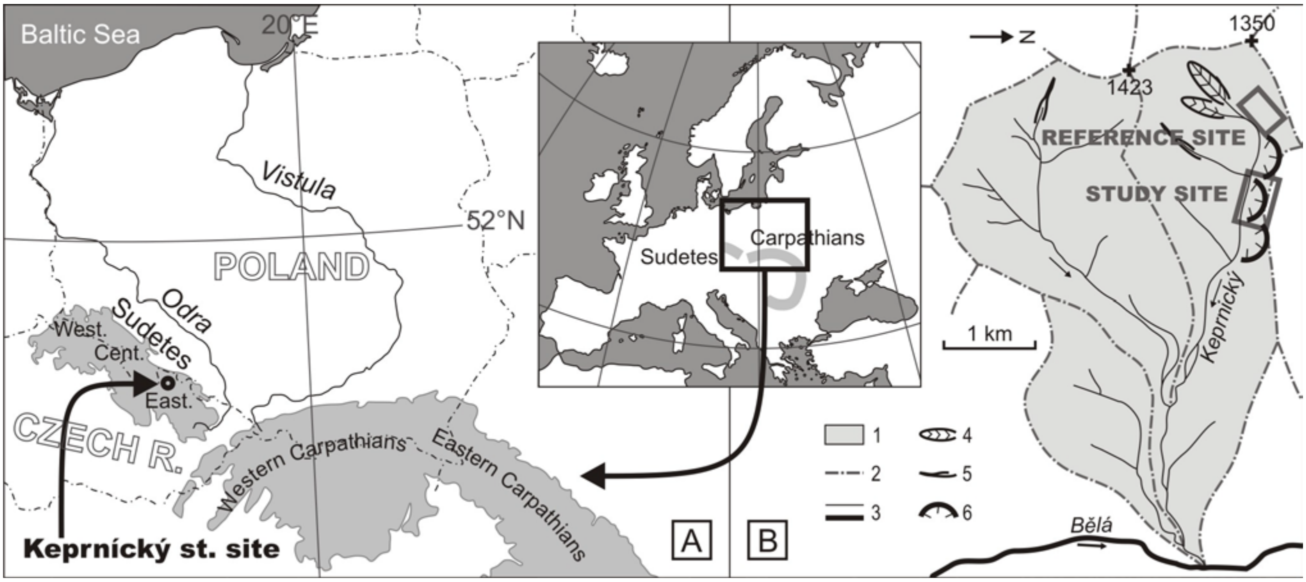

Fig. 6. *A – Location of the Keprnický study site in Central Europe, Eastern Sudetes and Czech Republic. B – Location of study and reference sites within the Keprnický stream catchment: 1 – catchment, 2 – watersheds, 3 – streams and rivers, 4 – debris flows, 5 – avalanche gullies, 6 – landslides.*

suggesting the presence of past or contemporary mass movement activity, probably deep-seated landslide. A reference site was also selected in the upper section of the Keprnický valley (Fig. 6). It is located in the immediate vicinity of the study site (1.0 km distant) on a slope with an orientation and inclination similar to those of the study site. The reference slope has a smooth surface and is presumed to be devoid of deep mass movements. Observations indicate that it is mainly being shaped by surface wash.

Both the study and reference sites belong to the montane mixed forest belt – the natural habitat of deciduous beech forest with common beech (Fagus sylvatica L.) and European silver fir (Abies alba Mill.) (Seneta and Dolatowski, 2008). Now sites are covered with artificially planted, monocultural forests with Norway spruce (Picea abies Karst.).

The landslide relief of the Keprnický study site

The site analysed is a landslide (~200 m long and ~300 m wide) descending from a mountain ridge (~910 m a.s.l.) into a valley floor and stream channel (~850 m a.s.l.). The site is located in the middle, transitional section of the valley. The study included a whole landslide, composed of a single niche and single tongue (Fig. 7A). The niche is rather steep, with inclination of up to 75%. It is covered with loose boulders (up to 2 m long), that are being pushed out of the slope. The landslide tongue consists of several lobes with steep heads, and flat rear sides. The lowermost part of the landslide tongue is being eroded by the Keprnický stream. The niche and tongue are both partially covered with active screes (Fig. 7A).

Methods of study

Two samples were taken from each tree using a Pressler borer. Cores were taken at breast height on one axis parallel to the slope inclination or to elongation of trunk cross-profile (if they were not exactly identical). The procedure applied enabled to obtain tree-ring data from the upslope and downslope parts of the trunks.

Only trees without visible loss in assimilation apparatus or trunk injuries were sampled. We have chosen trees that had the most deformed trunks possible. A total of 42 trees were taken on the landslide slope and another 12 at the reference site. All samples were taken from Norway spruce (Picea abies Karst.).

The cores were glued into wooden stands and sanded with abrasive paper. Widths of tree rings were measured with 0.01 mm precision. Data obtained for the up- and downslope sides of single trees were compared and converted into an eccentricity index of tree rings. On this basis, the most probable moments of landslide activation for the slopes studied were found by further calculation, using the formula 3 presented in section 4. The procedure for sample preparation and analysis was identical on the landslide and reference slopes. The reference results were considered as typical for stable slopes free from the impact of mass movements.

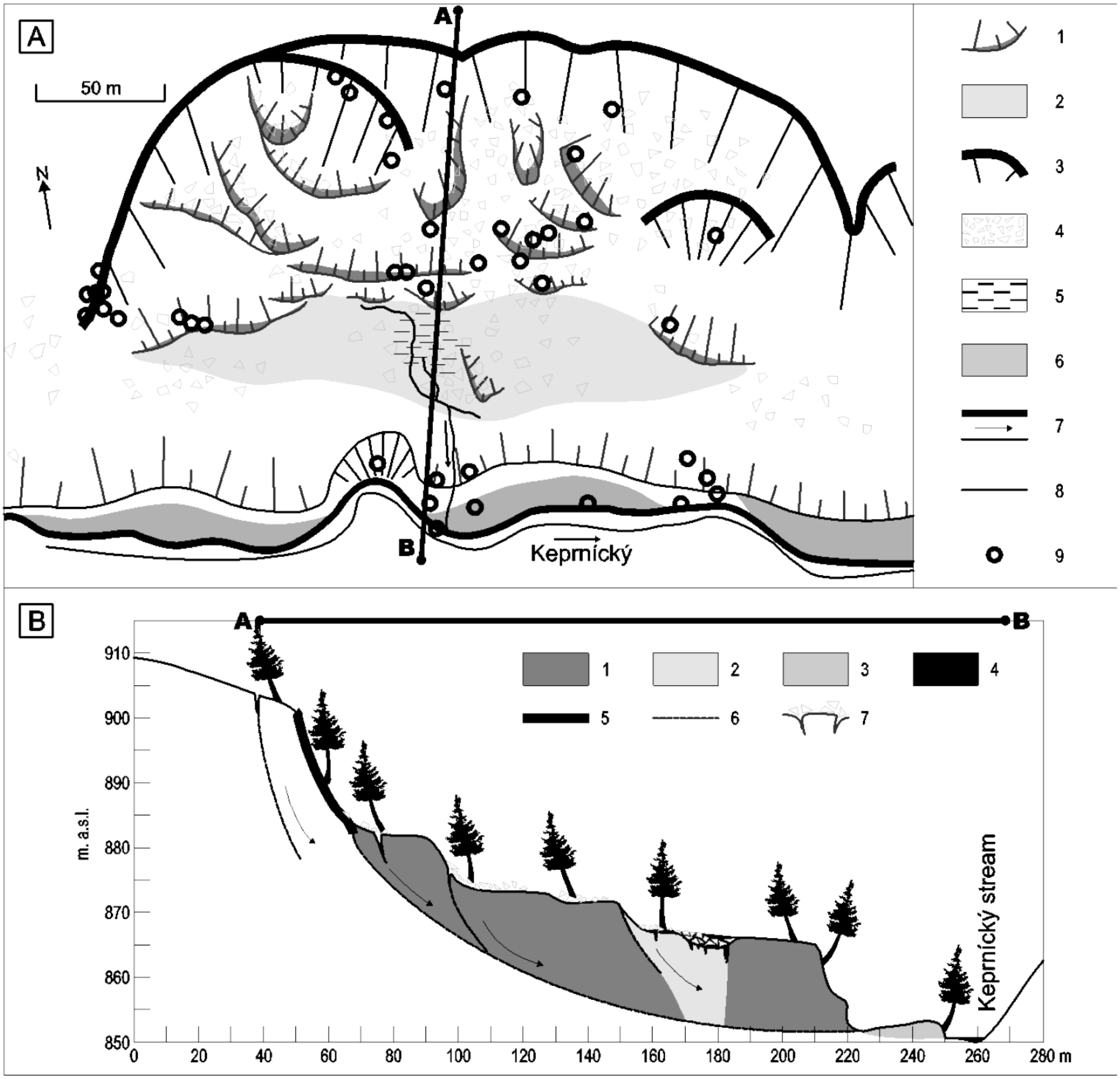

Fig. 7. *A – Geomorphic sketch of the Keprnický study site: 1 – landslide lobes, 2 – collapsed block, 3 – headscarp, 4 – scree slopes, 5 – boggy areas, 6 – alluvial bars, 7 – stream channels, 8 – bank undercuts, 9 – sampled trees. B – Landslide cross-section with general directions of tree tilting: 1 – landslide lobes, 2 – collapsed block, 3 – alluvial bar, 4 – water, 5 – headscarp, 6 – sliding surface, 7 – rock crevices and scree slopes.*

Tree-ring data derived from the landslide were compared with precipitation totals (Czech Hydro-Meteorological Institute, Ostrava, Czech Republic). Data were gathered from the gauging stations in Rejvíz (period: 1959-2000) and Heřmanovice (1963-2008) – 15 and 17 km from the study site. For the dendrogeomorphic analysis we have selected data for June, July, August and September – the months with the highest precipitation totals, which are probably responsible for activating mass movement in the region studied.

The deformation of tree stems at the Keprnický landslide

On the uppermost parts of the landslide studied spruce trees are, in general, bent upslope with straight stems. They are growing above the headscarp in the zone of active preparatory slope mass-movement: lateral spreading and initial landsliding (Fig. 7B). In the future another landslide is probable in this area. Trees observed on the main headscarp and the upper parts of the landslide tongue are growing on active scree slopes, on large boulders that are being squeezed out of the slope as a result of landsliding. These spruce are also tilted upslope but their stems are rarely straight, rather they are rotated, s-shaped or "pistol-butted" (**Fig. 7B**). The elongation of the trunk cross-profiles which does not match slope inclination proves that they have been deformed by several mass movement events of diverse directions (multiple tilting). Spruce growing on the flat, middle part of the landslide tongue have straight stems (**Fig. 7B**). Spruce trees growing on the lowermost landslide lobe are tilted in two directions: on the flat, upper surface they are bent upslope, but on the lower, steep part, which has an inclination towards the valley axis, they tilt downslope and have curved stems.

The general upslope direction of tree tilting in the major part of the site was developed under the impact of landslide movements. The downwards (channel) direction of the tilting in the valley bottom, on the banks of the Keprnický stream is an effect of lateral fluvial erosion in the near-channel zone – undercutting of the landslide toe during extreme floods (**Fig. 7B**).

A dendrochronological record of landsliding at the Keprnický site based on eccentricity index

The length of the series of tree ring data depends on the age of the trees sampled. At the Keprnický site the series of eccentricity data date back to the first half of 19th century. The oldest landsliding signal dated is 1836 (**Fig. 8**). 31 of the total 42 eccentricity series date back to at least 1900.

The patterns of eccentricity index for trees growing at the reference site as presented on the graphs are different from those obtained for the landslide slope (**Fig. 5**). The index values for spruce growing on stable slopes oscillate around 0%, rarely exceeding ±100% during the whole period of the trees' lives (as for instance in the example on **Fig. 5** in the first period before 1989). Individual years or few-year periods with upslope and downslope eccentricity occur alternately. This situation was interpreted as a record of a constant balancing of the tree, which maintains a near-vertical position and equilibrium on a slope. The balancing is the effect of the continuous need to fight the impact of deforming factors like: wind, snow cover, the increase in the mass of the tree with time due to its growth.

Some trees growing on the Keprnický landslide slope show the same pattern of eccentricity index as in the reference site in the first period of growth, oscillating around 0%. More or less abrupt change (increase or decrease) can be observed after that period (e.g. **Fig. 5**: stability before 1989 and later jumps of index value). At the Keprnický study site the maximum upslope eccentricity index value of a single annual ring is 3450.00%, in the case of downslope eccentricity it is -1011.43%. Moments of abrupt change of eccentricity can be interpreted as sudden disturbances of equilibrium as for example the tilting of trees due to the activation of gravitational mass-movements. Some trees sampled do not show the initial period of stability described. Values of eccentricity are already very high or very low in the first years of tree growth, which proves that from the beginning of their lives the bedrock was unstable.

Threshold values were calculated on the basis of eccentricity data from the reference slope in order to determine episodes when probably landsliding was activated (e.g.: **Fig. 5**). The threshold for downslope eccentricity is -59.54%, the one for upslope eccentricity is 56.38%.

The total number of mass-movement episodes found with the use of the above-mentioned thresholds is: 697 (in 42 trees, during 174 years). 574 of these (82.35%) are upslope episodes. The temporal distribution of landsliding episodes is uneven (**Fig. 8**). In general it increases along the time axis from 1836 to 2001 in time with the increase in the number of available time series. The first peak period of landslide activity at the Keprnický site is 1918-1944 (up to 7 signals per year), with an escalation in 1934-1939. The second one is: 1958-2001 (up to 15 signals per year) with increased intensity in 1971-1999.

With precipitation data available, the period of 1959-2008, was chosen for detailed analyses of the relation between eccentricity/landsliding episodes and meteorological conditions.

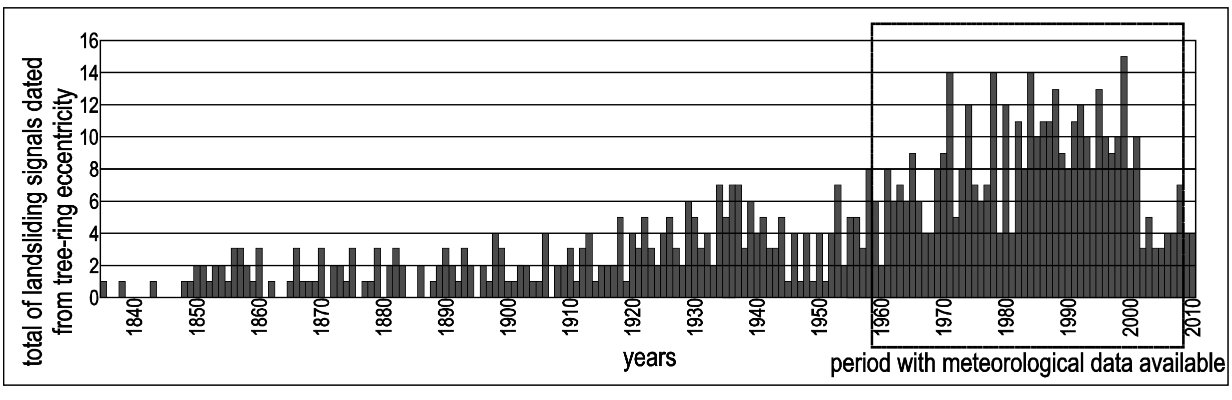

Fig. 8. *Landsliding signals dated from tree-ring series from the Keprnický study site for the period 1835-2010.*

Temporal variability of landslide episodes at the Keprnický site compared with precipitation data

Temporal variability of landslide activity, determined on the basis of the eccentricity of tree rings, can be presented in several ways. The total number of eccentricity/landsliding episodes (dated using established thresholds) per year can be shown on a bar graph (**Figs 8-9**). It can also be divided into separately presented numbers of upslope and downslope episodes. The average intensity of signals detected for a certain year can also be presented on a bar graph (**Fig. 9**) with upslope (positive) and downslope (negative) values separated. Intensity is an arithmetical mean, which includes values of the yearly variation for certain years/annual rings in certain samples, for which mass-movement episodes were already identified (based on thresholds, e.g. values for 11 signals from in 11 samples in 1991 – **Fig. 9**). Contrary to the number of signals, the average intensity is independent of the number of trees growing in a certain year – values of intensity are comparable over the whole of the period analysed.

Graphically presented eccentricity indicators can be compared with the precipitation record (**Fig. 9**). In case of the Keprnický landslide, the highest number (15) of eccentricity signals was found for year 1999, when total precipitation for June in the area was above average. Two preceding years, 1997 and 1998, are well known for their catastrophic summer floods. Despite that, the amount and intensity of eccentricity signals was not high then. It may be that the initial mass movements took place in 1997-1998, and, by increasing bedrock instability, prepared the slope for landsliding in 1999.

A clear example of landsliding signals caused by high precipitation is 1980 (12 signals) with high precipitation in July (**Fig. 9**). However, years with a great number of eccentricity episodes are not always characterized by high monthly precipitation, for instance 1971 (14 signals), 1974 (12), 1978 (14), 1984 (14), 1988 (13), 1992 (12), 1995 (13). It is perhaps an effect of great local variability of precipitation, especially summer storms. It is also a proof that landsliding can probably be triggered by a single downpour that does not influence the total monthly amount of precipitation (only slightly exceeding average values: **Fig. 9**).

The significance of local storms can be confirmed by the relationship of signal intensity to precipitation data (**Fig. 9**). Landsliding episodes with the highest/lowest (up-/downslope) intensity of signals do not coincide with the years of highest precipitation. Years with above-average intensity are: 1968 (upslope signals >200%), 1971, 1975 (downslope <-200%), 1984-5, 1988, 1991-2, 1994, 1999, 2001, 2004-5, 2007 (upslope >200%). The explanation of this is likely to be the occurrence of abrupt, catastrophic, but local rainfall events, like those in:

- April 1971 – which, according to Štekl *et al.* (2001), were catastrophic in the Keprnický valley area, but were not recorded in gauging stations 15-17 km distant,
- July 1991 – when monthly precipitation hardly exceeded average values (**Fig. 9**), but a catastrophic rainfall was observed in the study area, together with the activation of mass movements – debris flows (Gába, 1992).

It can also be observed from the data obtained (**Fig. 9**) that high intensity landsliding signals occur in years with generally wet summers (monthly precipitation totals were above avg. in June-August): 1968, 1972, 1975, 1989, 1999.

The years 1980 (strong up- and downslope signals), 1985, 1997 (upslope) are exceptions with high rainfall totals and relevant intensity of signals. Despite that, the highest precipitation (1997) and highest number of signals (1999) is not accompanied by high intensity. In some cases high numbers of mass movement signals are recorded one or two years after the years in which rainfall events were recorded, examples (**Fig. 9**) include the above mentioned year 1999 after catastrophic summer floods in 1997-8, 1988 after a wet August in 1987, 1992 after catastrophic rainfall in July 1991. The reasons for such situations can be:

- increased slope instability after initial mass movements during the catastrophic rainfall event (landslides can be triggered by smaller precipitation in following years, as probably occurred in 1997-9),
- a prolonged, strong tree reaction caused by a particularly catastrophic event in the first year (as probably occurred in 1991-2),
- landsliding at the end of the growing season so that the tree reaction is lagged to the beginning of the following spring (as probably occurred in 1987-1988 following rainfalls in August 1987).

Spatial variability of landsliding in Keprnický site

The presentation of the eccentricity data obtained from the Keprnický landslide on maps (where the circle radii match the value of the eccentricity index in each sample in the selected year – **Fig. 10**) enable the analysis of the spatial distribution of mass movement episodes. The situation in 1990-2, in the years in which the highest intensity of landslide signals occurred, was analysed. In general, the maps created have shown that the mass movement activity in the period analysed was highest in the upper and central parts of the landslide. After a rainfall event in the first year, the central section (parallel to the slope inclination) of the landslide was activated in the following year (**Fig. 10**). The lowest parts of the landslide were stable; channel erosion during rainfall event did not disturb the equilibrium of this parts of the slope.

Spatial distribution of eccentricity record confirmed observations on deformations of tree stems (**Section 5 – The deformation of tree stems at the Keprnický landslide**). In the near-channel zone influenced by fluvial erosion downslope eccentricity dominates and above, on the slope where landsliding occurs, upslope eccentricity is dominant with only a few exceptions (**Fig. 7B**, **Fig. 10**).

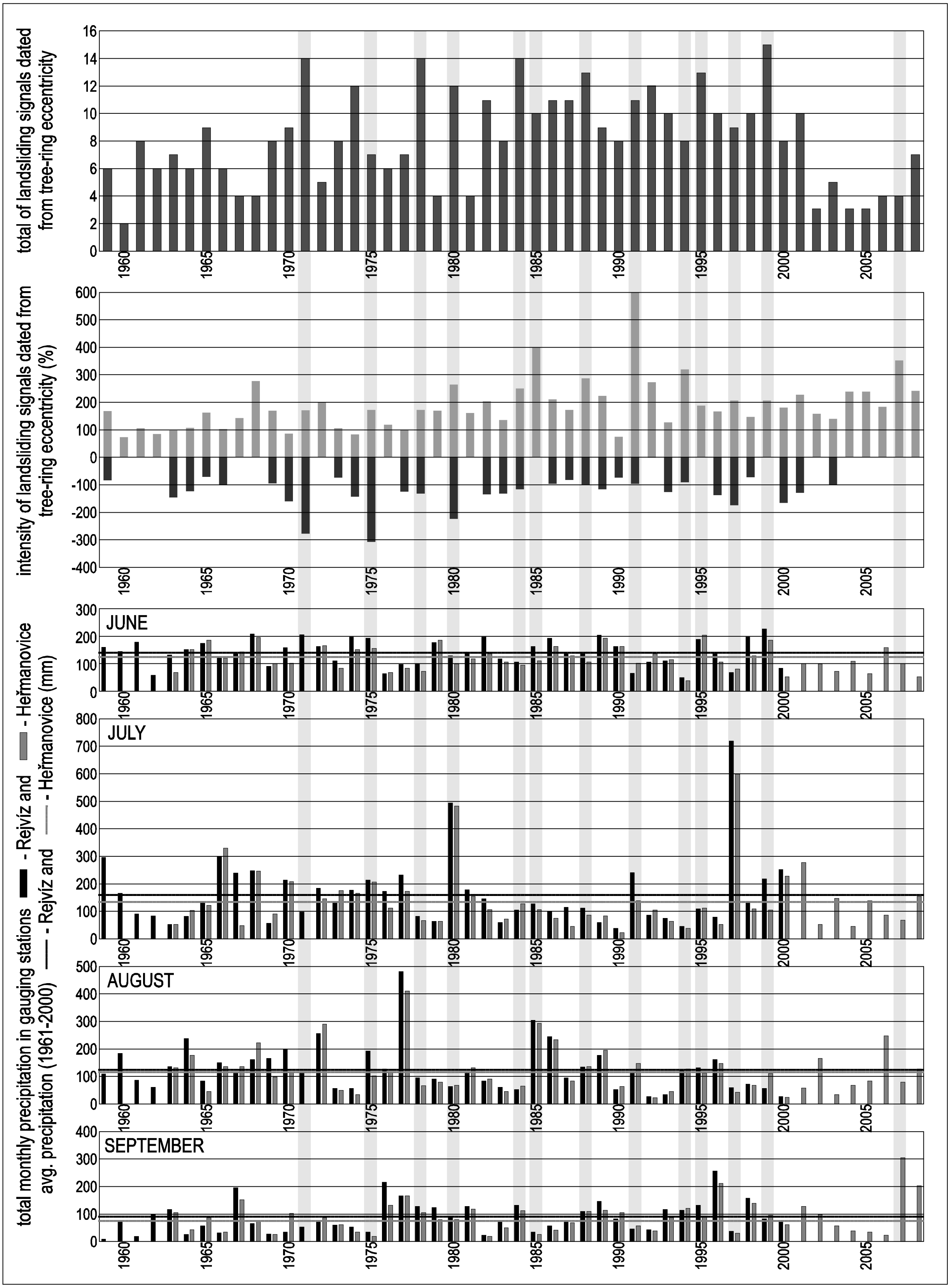

Fig. 9. *Comparison of number and intensity of landsliding signals dated at the Keprnický study site with precipitation data for the period 1959-2008 (light grey stripes – years with highest number and/or intensity of signals or with highest precipitation totals).*

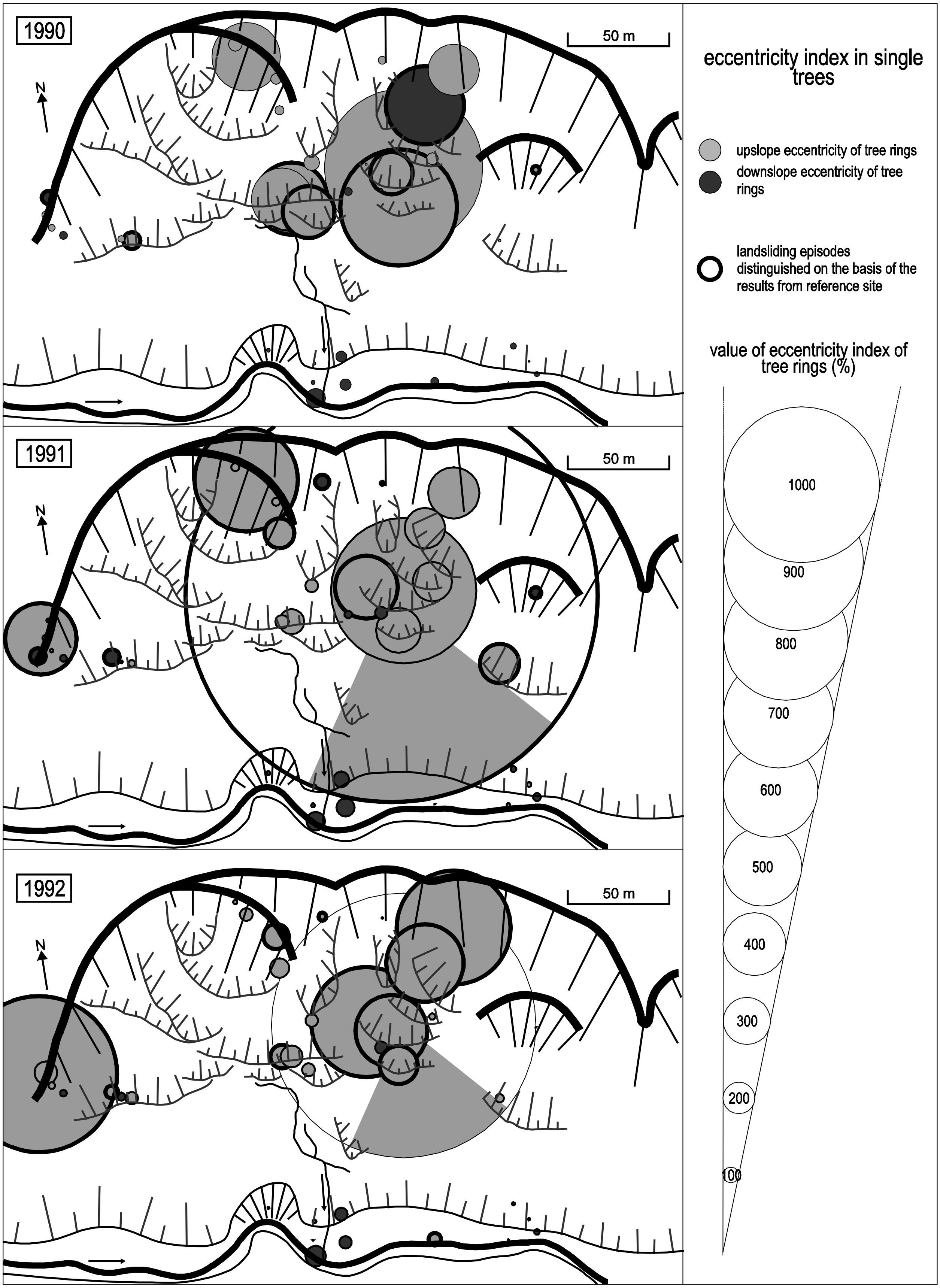

Fig. 10. *Tree-ring eccentricity values in trees sampled in the Keprnický study site for the years 1990-1992.*

6. CONCLUSIONS

1) Tree ring analyses are increasingly frequently used for mass-movement studies. The most important advantage of the dendrogeomorphic method is the possibility of reconstructing the spatial and temporal variability of mass-movement events with at least one year resolution.
2) Trees record different types of mass-movements in their wood anatomy:
   - Trees growing on slopes, where landslides occur, are tilted or bent. After the landslide event trees produce reaction wood and eccentric rings. The oldest ring recording these wood features marks the date of the event.
   - Trees growing along debris-flow tracks or on scree slopes, where rock material is being transported can be wounded by rock particles. Counting of the number of years elapsed after wounding enables one to date debris flow and rock fall events.
   - Stems of trees growing on the lower parts of debris flow tracks can be buried with sediment. Determining the age of adventitious roots growing in the sediment enables one to estimate the moment when debris flow occurred.
   - The roots of trees growing on landslide or debris-flow slopes can be exposed out of the soil and sediment cover. Counting the number of rings with smaller cells and late wood formed after root exposure allows to date landslide or debris flow events.
3) The method presented for the dendrochronological analysis of landslides, based on growth eccentricity, was designed for the needs of geomorphology. It is based on field observations; it includes and benefits from the variety of stem shapes developed when spruce trees are growing on unstable bedrock or sediment.
4) Analyses carried out using tree-ring eccentricity allow, in contrast to the popular, classical methods (e.g. geomorphic mapping, geophysical sounding, lichenometric and radiometric dating), to obtain a dynamic depiction of slopes studied. In contrast to remote sensing systems and geodetic monitoring, it allows one to study the activity of landsliding slopes, not only in contemporary times, but also in the last tens or hundreds of years (depending on the age of the stand).

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