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Bank erosion history of a mountain stream determined by means of anatomical changes in exposed tree roots over the last 100 years (Bílá Opava River — Czech Republic)

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Abstract

The date of exposure of spruce roots as a result of bank erosion was investigated on the Bílá Opava River in the northeastern Czech Republic. Following the exposure of roots, wood cells in the tree rings divide into early wood and late wood. Root cells within the tree rings also become smaller and more numerous. These processes permit dating of the erosion episodes in which roots were exposed. Sixty root samples were taken from seven sampling sites selected on two riverbed reaches. The results of root exposure dating were compared to historical data on hydrological flooding. Using the root exposure dating method, several erosion episodes were recorded for the last 100 years. The greatest bank erosion was recorded as consequence of an extraordinary flood in July 1997. In the upper, rocky part of the valley studied, bank erosion often took place during large floods that occurred in the early 20th century. In the lower, alluvial part of the valley, erosion in the exposed roots was recorded only in 1973 and has been intensive ever since. It is suggested that banks in the lower part are more frequently undercut, which leads to the falling of trees within whose roots older erosion episodes were recorded. Locally, bank erosion is often intensified by the position of 1- to 2-m boulders in the riverbed, which direct water into the parts of the banks where erosion occurs. Selective bank erosion could be intensified by debris dams and hillslope material supply to the riverbed.

Keywords: Bank erosion; Mountain stream; Dendrogeomorphology; Exposed roots

1. Introduction

The rate of bank erosion in mountain streams mainly depends on the bank material erodibility and the history of fluvial processes, particularly the character and frequency of high water episodes (Gregory and Walling, 1973; Krzemień, 1976; Thorne, 1982; Starkel, 2002). What is also of considerable importance for the erosion of banks composed of loose rocks is the activity of needle ice and ice floats, as well as the nature of the riparian vegetation (Klimek, 1989). Banks strengthened by root systems are more resistant to washing out and less undercut as compared to those without vegetation cover (Sttot, 1997; Rowntree and Dollar, 1999, Abernethy and Rutherfurd, 2000). Banks not strengthened by tree roots are by half more erodible than banks with root systems. Roots of riparian trees protect banks against erosion more effectively than species inhabiting non-riparian zones (Pollen and Simon, 2005).

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In order to define the history of bank erosion in riverbeds of mountain streams, a number of field methods are used (Thorne, 1981). Erosion pins and geodetic methods, e.g., repeated riverbed cross-section (Harvey, 1974; Lawler, 1978; Hooke, 1980; Lane et al., 1994) are used in short, several-year-long, study periods. Another way of estimating bank erosion intensity is the analysis of riverbed morphologies on maps and air photos of various ages (Trafas, 1975). However, the method is applied most frequently for medium-sized and large rivers with a riverbed at least several meters wide. Also, photo-electronic erosion pins (PEEP) can be applied, these based on photographs of the bank taken automatically during erosion episodes (Lawler, 1991, 2005). The analysis of anatomical changes within the wood of trees growing on the undercut levels allows flood frequency, and indirectly bank erosion rate, to be reconstructed (Sigafoos, 1964; Hupp and Osterkamp, 1996). A lot of information may be provided by the analysis of coarse woody debris (CWD) lying *in situ* under erosional undercuts (Malik, 2005, 2006). However, high discharges occur in mountain streams and CWD is most often redeposited, which prevents the drawing of conclusions about bank erosion intensity at particular sites (Wyżga and Zawiejska, 2005). It seems that the exposed roots of trees overgrowing rock-and-regolith banks, floodplains, and terraces, are a much more valuable material for the analysis of bank erosion rate in mountain streams.

Dendrogeomorphological studies focused on root exposure dating as a tool for calculating erosion rate are few. LaMarche (1966) found a correlation between the distance from the exposed root to actual soil level and by age of the root and used this information to calculate the slope erosion rate. Alestalo (1971) noted the morphological changes in the wood anatomy of roots occurring in reaction to changes from aerial to subaerial environments or *vice versa*. During successive tree root exposure, ring reduction (suppression) often occurs, sometimes masked by release resulting from the elimination of competition from nearby trees (Alestalo, 1971). Shroder (1980) and Strunk (1997) have also described the effect of sediment burial on the production of adventitious roots. The age of the adventitious roots enables the year in which the deposition occurred to be identified. Different event types occur within root cross-sections, such as width, density, reaction wood, and corrasion scars (Shroder, 1978, 1980; Shroder and Butler, 1987). Those types of events can provide information about erosion intensity.

Carrara and Carroll (1979) also calculated erosion rates by examining exposed roots. They used tree root anatomical features to identify the years in which erosion occurred. The study was based on the time of initial cambium dieback, interpretation of annual ring growth patterns, and the earliest occurrence of reaction wood. Cross-dating of root samples was used to estimate gully erosion rates by Vandekerckhove et al. (2001). The authors suggest that a large number of samples are required to understand gully evolution. In order to estimate precisely the gully erosion volume, samples should be collected from various places on the exposed root, depending on its position (Vandekerckhove et al., 2001). Cross-dating of tree ring series from trees and roots allows identification of the year when an erosion episode occurred. Scars on roots produced by transported material may also inform about the occurrence of geomorphic events.

Roots document erosion episodes that have led to their exposure. Exposed parts of the root undergo anatomical changes. Tree rings occurring in roots after exposure are wider, cells are clearly smaller and there are many more of them. In addition the division into early and late wood is often clearly marked (Gärtner et al., 2001). Clear visible anatomical changes are recorded after exposure of coniferous tree roots (Hitz et al., 2006). Erosion analysis is best performed on live exposed roots documenting the exact year where root exposure occurred. Dead roots only document the minimum time passed from exposure and a simultaneous erosion episode (Malik, 2006).

In this study, the authors assumed that it is possible to reconstruct bank erosion history by examining the anatomical changes in exposed tree roots. The purpose of this study is (i) to determine how many and which exposed roots – depending on their position related to the river bank and soil – are particularly useful in riverbank erosion dating; (ii) to explain anatomical changes in exposed roots in relation to bank erosion processes; (iii) to identify sources of error in the root exposure dating process; and (iv) to determine the bank erosion history in mountain streams using exposed roots dating based on the example of the Bílá Opava River.

2. Study area

The Bílá Opava River valley is located in the northeastern part of the Czech Republic, in the Hrubý Jeseník massif (Eastern Sudetes). The elevation of the massif is 1000–1500 m a.s.l. (Fig. 1a–c). Along the upper course of the Bílá Opava River drainage basin, the Hrubý Jeseník massif consists primarily of Devonian orthogneiss, local migmatites and – in the upper parts – fine- and medium-grained paragneiss. The northern

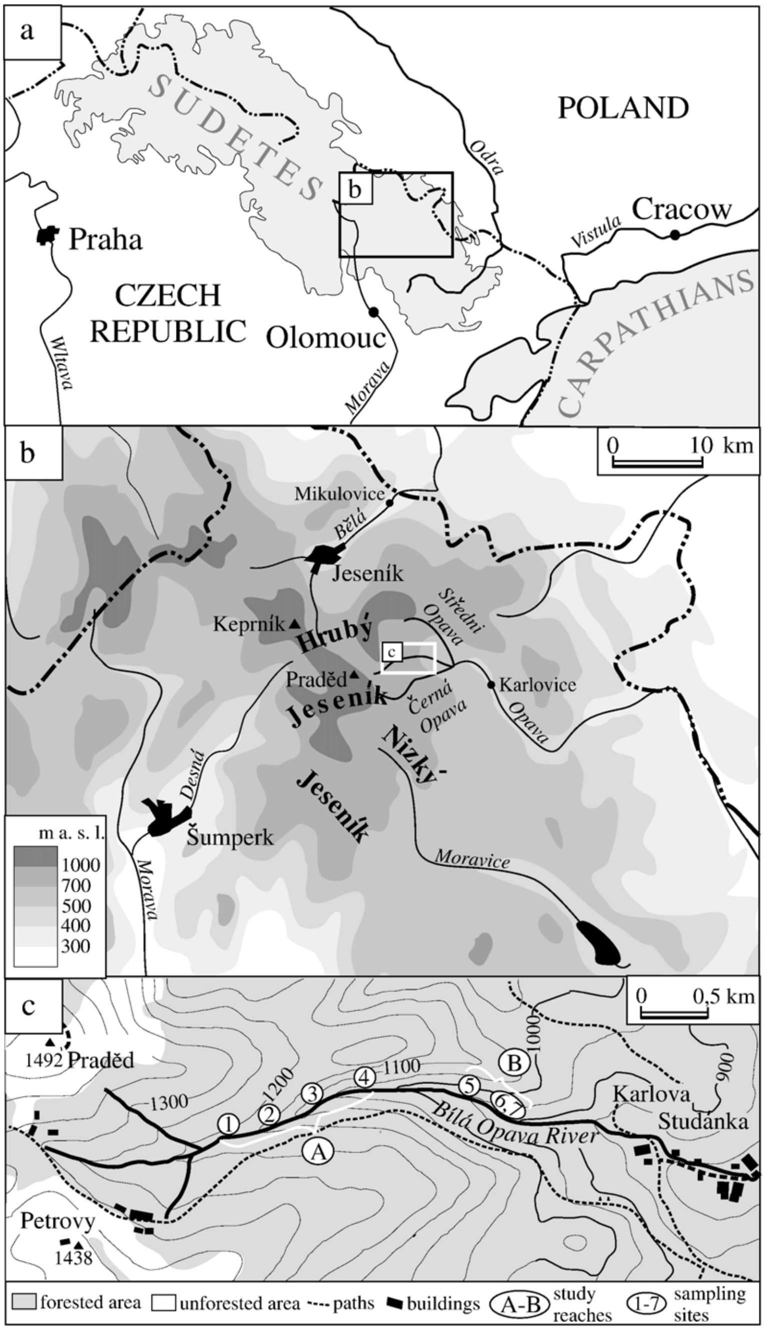

Fig. 1. (a) Location of study area and sampling sites in Central Europe, (b) in the Jeseniki Mountains, (c) in the Bílá Opava River Valley.

foothills of the Sudetes were probably twice covered by the Scandinavian ice sheet. At that time the study area was subject to a periglacial climate and intensive mechanical weathering occurred. As a result of this process regolith covers were formed. Regolith is mainly transported by debris flow to the riverbeds of streams flowing in the Hrubý Jeseník Massif. Debris flow delivery zones can be several meters wide and up to 800 m long (Gába, 1992; Migoń et al., 2002).

The Bílá Opava River valley, in its upper course, cuts about 200–300 m into the eastern face of the Praded Massif. Seven sites were selected here in two river reaches (Fig. 1c). Sites I–V were located in the upper reach studied A; (Fig. 1c) where the average valley gradient amounts to 13°, valley hillslopes even reach a gradient of 50°, and the valley width reaches up to 20 m. Numerous waterfalls on quartz vein outcrops occur in the riverbed. On steep hillslopes distinct debris flow tracks occur which document sediment yield to the riverbed. Banks are usually formed of rock; hence factors enhancing root exposure may here include biomechanical weathering. Growing roots also expand in width, which leads to loosening rocky material. As a result of bank erosion the material is carried away.

Sites V–VII are situated in the lower part of the reach studied B, where the average valley gradient amounts to 8°, hillslopes reach a gradient of 35°, and the valley width reaches up to 80 m. The majority of banks are formed of alluvial material. Numerous quartz, quartzite and gneiss boulders up to 2 m across are deposited in the riverbed forming a typical braided pattern. The riverbed is characterized by a large quantity of CWD.

The average annual precipitation in the Hrubý Jeseník Massif is about 1500 mm. A large part of the intensive precipitation is linked to specific meteorological situations, in which cyclones arriving from the direction of Central or Northeastern Europe create favourable conditions for continuous heavy precipitation, especially between June and August. Maximal intensity of rainfall (300 mm/2 h) occurred in Hrubý Jeseník on the 1st of June 1921 (Štekl et al., 2001). During heavy precipitation events large floods occur, dozens of which have taken place in the Hrubý Jeseník Massif in the last 500 years (Polách and Gába, 1998). Particularly frequent floods occurred at the turn of the 20th century. One of the largest was the flood of 1903, when the valley floor morphology of Bílá Opava was transformed. Numerous sub-fossil braided river patterns with residual boulders were dated dendrochronologically to the first decade of the 20th century (Klimek et al., 2003). The analysis of post-flood damage performed by Polách and Gába (1998) in historical sources showed that floods and high precipitation events occurred within a radius of several kilometers from the reach studied in the years 1910, 1913, 1914, 1921, 1930, 1931, 1940, 1948, 1958, 1966, 1972 and 1977. Water flow from the drainage basin of the Bílá Opava, Støedni Opava, and Èerná Opava streams is recorded at the hydrological gauge in Karlowice, located 15 km east of the reach of the Bílá Opava studied (Fig. 1b). This station recorded high maximum monthly discharge rates in 1977 (76.1 m^3/s), 1980 (77.1 m^3/s), 1985 (46.1 m^3/s), and 1996 (50.1 m^3/s). However, the highest discharge (320 m^3/s) was registered in July 1997 during an extraordinary flood which ranged over the entire Central Europe.

Forest clearance has been practised in the mountain reaches of the Bílá Opava River drainage basin since the Middle Ages when copper smelters existed there. Hence the area studied was periodically deforested in the past (Klimek, 2005; Latocha, 2005). At the present time, the tree line (1400–1430 m a.s.l.) is composed of natural communities of spruce that gradually grade into mountain pine (*Pinus mughus*). The reaches of the valley studied are vegetated with spruce plantation (*Picea abies*), the oldest of which are about 110 years old.

According to a map of 1780, there was a water reservoir in this reach of the Bílá Opava fed by springs above the study sites. Timber from trees felled above was rafted downstream when water was released from the reservoir. The reservoir no longer existed in the mid-19th century, as testified by the map of 1841.

3. Methods

The roots of spruce growing on the valley bottom of the Bílá Opava River are exposed due to erosion (Fig. 2). Exposure dating made it possible to determine the time when intensive erosion occurred at the sites under examination. In March 2004, before collecting samples in the study area, the authors exposed dozens of spruce roots in order to monitor changes in anatomical features occurring after exposure. The experimental trees grew in the Silesian Highlands in southern Poland in limestone soil. One year after exposure, every tree produced clearly marked tree rings divided into early and late wood with small, numerous cells. This means that spruce are capable of producing annual rings with anatomical changes after exposure.

At 7 sites located on the valley floor of the Bílá Opava, 60 samples were taken from 23 roots among the exposed roots of spruce trees growing in the vicinity of undercut banks. Roots were mostly exposed in the bank area (sites I, III, IV V and VI), in the case of a spruce tree at site II, on the hillslope over a dry riverbed, and at site VII, in an area of terrace levels. All samples were collected in November 2004, that is after the trees had developed full annual tree rings. Using a pole and measuring tape, forms of valley floor were mapped 15–20 m above and below each place where exposed root samples were collected. Using a clinometer, hillslope was defined at the sites where exposed root samples were collected.

Samples of 5- to 10-cm fragments of living exposed spruce roots were taken using a handsaw. When more roots at the site were exposed in a similar position (distance from the bank and altitude above riverbed),

Fig. 2. Photograph showing exposed spruce roots in the Bílá Opava riverbed.

samples were taken from the thickest roots possible. Where conditions permitted, samples were taken from exposed parts of the roots 10 to 30 cm apart. From two to five samples were taken from each root depending on its length. Moreover, root orientation was compared to the bank line in three directions: vertical, horizontal, oblique. Also, root height above riverbed level was defined as was its distance from the undercut surface.

All samples were cut by knives to examine the structure of the wood in cross-section. The location where the root became exposed was determined using a binocular microscope, based on the assumption that the moment of exposure was marked by a sharp decline in cell size and an increase in the number of cells. The time of exposure was calculated by counting the number of tree rings younger than the first at which anatomical changes were found. Information from previous works shows the possibility of multiple counting directions across samples (Shroder, 1980; Shroder and Butler, 1987). In this study calculation of tree rings was performed along the longest possible radius of the root cross-section, so as to include the wedging tree rings (Schweingruber, 1996).

In the case of 18 samples taken from roots, the use of a binocular microscope with a rather small magnification proved insufficient to precisely define the year of exposure. The year of exposure of these samples was identified using a traditional microscope. Slices of wood 15–20 μm thick were cut by means of a microtome. The length of slices of wood was calculated from the distance between the root centre and the last of its tree rings on the longest radius possible. The width of each wood slice amounted to approximately 0.5 cm. Therefore, in the largest samples, several slices were prepared. The number of tree rings with anatomical changes visible under the microscope defined the root exposure time.

4. Results and discussion

Sites I–V are located in reach A, 500–2050 m below the source of the Bílá Opava. The width of the valley floors varies from 2 to 20 m (Figs. 5 and 6; Table 1). The gradient of the valley hillslopes is 30–45°. The riverbed cuts into bedrock and is mainly composed of gravelly deposits. Sometimes boulders up to 2 m in diameter accumulate in the riverbed. Two terraces of 0.8 and

Table 1
Morphological features of the studied sites

Reach and site number	Location of sites studied below river spring (m)	Gradient of adjacent hillslopes	Valley width (m)
AI	500	30–40°	2–8
AII	750	30°	2–8
AIII	1150	30–40°	4–10
AIV	1500	30–45°	8–20
AV	2050	35–40°	8–15
BVI	2300	25–35°	20–45
BVII	2620	30–35°	50–80

2–2.2 m occur at sites IV and V. Numerous steps on bedrock outcrops, boulders, and CWD are located in the riverbed (Figs. 3 and 4; Table 1).

In total, 27 samples from 12 roots were taken at sites I–V. Most were horizontally oriented. The sampled roots grew from 0.2 to 0.8 m above the riverbed floor and the distance between roots and cutting banks was 0.05–0.6 m (Table 2). As many as 12 root samples were exposed in 1997, whereas the oldest root exposure took place in 1912 (Table 2).

Sites VI and VII are located in reach B, 2300–2620 m below the source of the Bílá Opava River. The width of the valley floor varies from 20 to 80 m. The gradient of the valley hillslopes is 25–35°. Terraces

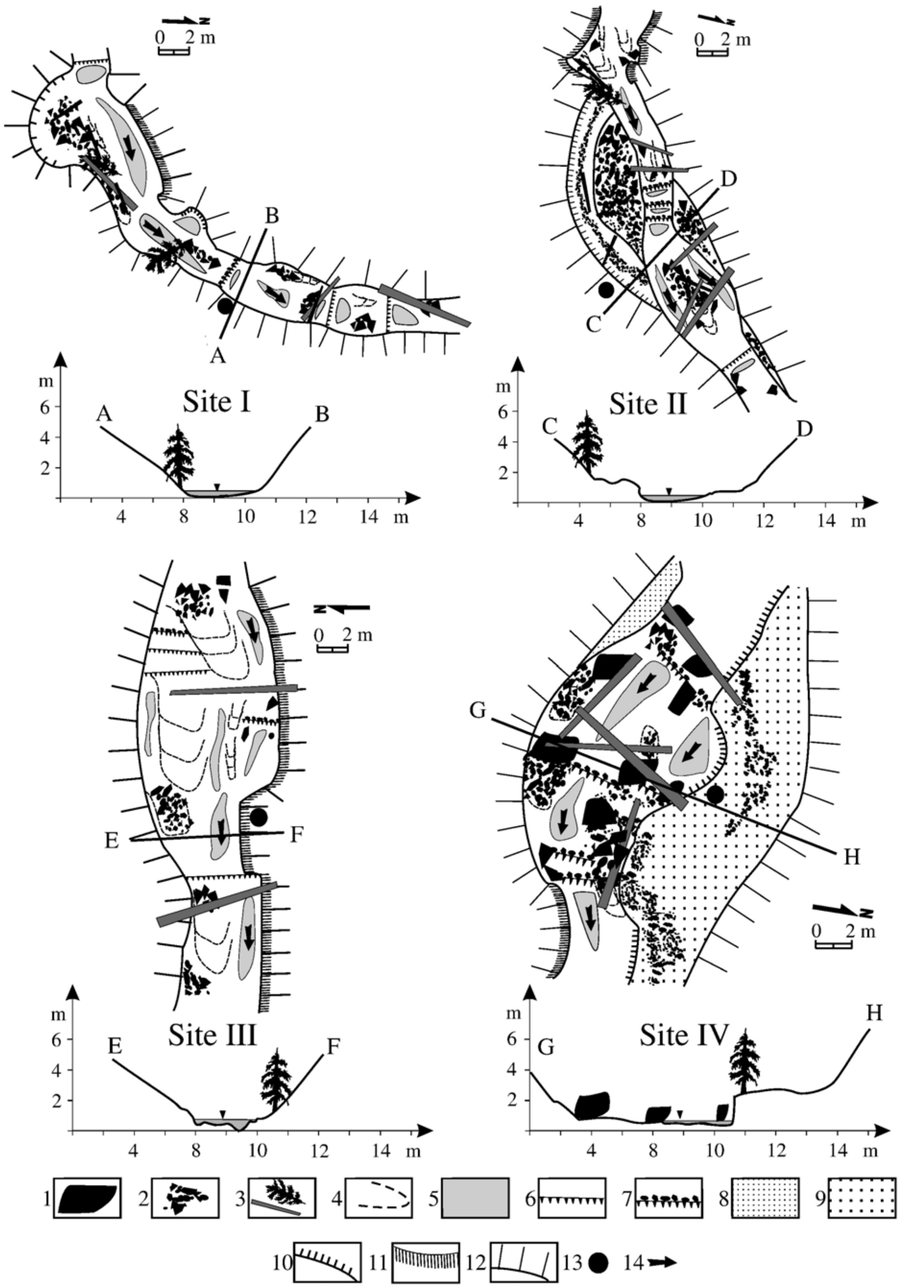

Fig. 3. Geomorphological sketches of the Bílá Opava River Valley floor at sampling sites I–IV. 1 — boulders above 1 m in diameter, 2 — gravelly deposits, 3 — coarse woody debris, 4 — spurs and rock ribs, 5 — pools, 6 — rocky steps, 7 — debris steps, 8 — terraces to 1.5 m, 9 — terraces of 1.5–2.5 m, 10 — erosional edges, 11 — bank rocky outcrops, 12 — hillslopes, 13 — sampled spruces, 14 — flow direction.

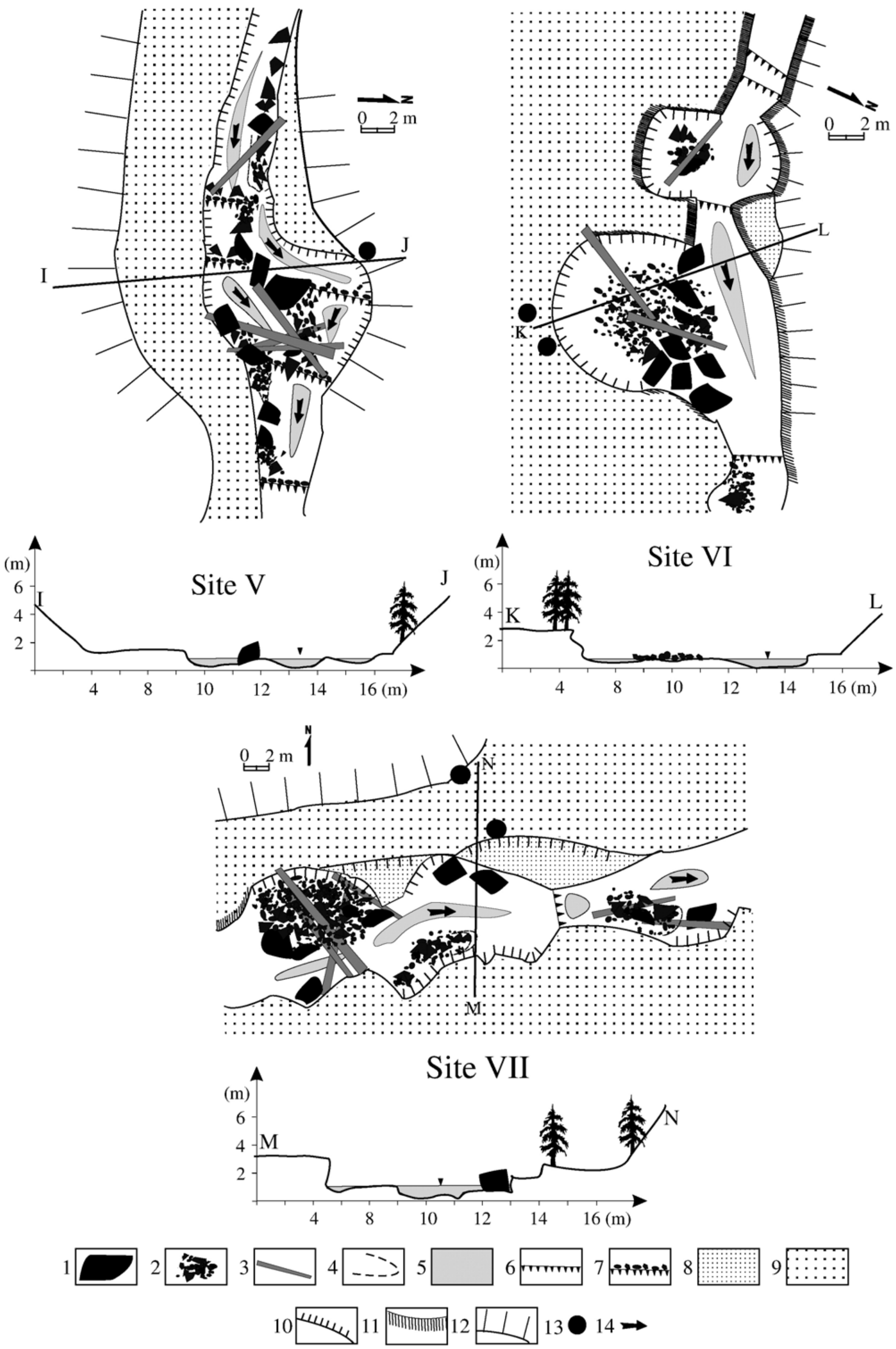

Fig. 4. Geomorphological sketches of the Bílá Opava River Valley floor at sampling sites V–VII. 1 — boulders above 1 m in diameter, 2 — gravelly deposits, 3 — coarse woody debris, 4 — spurs and rock ribs, 5 — pools, 6 — rocky steps, 7 — debris steps, 8 — terraces to 2 m, 9 — terraces of 2–4 m, 10 — erosional edges, 11 — bank rocky outcrops, 12 — hillslopes, 13 — sampled spruces, 14 — flow direction.

Table 2
Position, height, distance and the year of exposure of the roots in reach A

Site number	Root number and piece of root number		Exposed root length (m)	Root orientation	Height above the riverbed (m)	Distance from cutting surface (m)	Most probable year of exposure
AI	1	a	0.6	Vertical	0.2–0.5	0.3	1997
		b				0.5	1997
	2	a	0.4		0.7–0.9	0.4	1997
		b				0.2	1967
AII	3	a	0.5	Horizontal	2.4	0.5	1912
		b				0.1	1958
AIII	4	a	0.7	Vertical	0.9–1.5	0.05	1997
		b				0.05	1997
		c				0.15	1993
	5	a	0.6	Horizontal	1	0.5	1949
		b				0.3	1997
	6	a	0.5	Oblique	0.6–0.8	0.5	1931
		b				0.2	1997
	7	a	0.7	Horizontal	0.8	0.4	1958
		b				0.2	1997
	8	a	0.4	Oblique	0.6–0.8	0.3	1964
		b				0.1	1993–95
AIV	9	a	0.6	Horizontal	1	0.6	1988
		b				0.4	1990
		c				0.2	1992–94
	10	a	0.3	Vertical	0.3–0.5	0.4	1957–58
		b				0.3	1960–62
AV	11	a	0.7	Oblique	0.4–0.8	0.3	1988–1989
		b				0.5	1997–1998
	12	a	1.1	Horizontal	0.8	0.3	1997
		b				0.4	1997
		c				0.2	1997

at 2–2.8 m and 3–3.8 m occur in this reach. The riverbed contains numerous boulders of over 2 m in diameter, which form steps and in which debris dams often occur (Fig. 4; Table 1). At sites VI and VII, 33 samples from 11 roots were collected. Most were oblique and horizontally oriented. The roots grew 1.8–2.8 above the riverbed floor and were longer (0.25–1.4 m) than roots in reach A (Table 3). The roots recorded erosion episodes between 1973 and 1997; most often root exposure took place in 1977, 1983 and, as in reach A, in 1997.

4.1. Validity and reliability of bank erosion dating using anatomical changes in tree roots after exposure

The sampling of sites/trees should be conducted at regular distances from each other in the longitudinal profile of the studied valley. This sampling strategy helps to identify real differences in erosion intensity in the studied valley. The minimum tree density to ensure a sufficient number of sample trees depends on the exposure intensity in the valley floor. It appears that sampling about 25% of the exposed roots is sufficient to measure bank erosion intensity in the studied valley because the remaining roots are in a similar or the same position as the sampled roots and most likely recording the same erosion events. If trees are lacking in certain riverbank sections, observations of bank width and structure are needed. If a riverbed section without trees growing on its banks – and thus without exposed roots – is relatively wider than sections up- and downstream, it is likely that the trees growing on the banks were undercut and transported. Additionally, if erodible rocks or especially older alluvium occur in the banks, the probability that the trees that had grown on the banks were transported downstream increases. By assuming that part of the logs give a testimony as to bank erosion in valleys where CWD is not cleared, in the future root exposure dating can be connected with log dating to improve the identification of the bank erosion process.

The Bílá Opava valley floor contains places where the trees are sufficiently distant from the banks being studied that bank erosion does not cause root exposure. When analyzing the degree of afforestation of the valley floor, it appears that root systems cover at least half of the valley floor surface in reach A. In reach B, sometimes trees do not grow on the valley floor or are scarce and do not cover more than 20% of the surface. In the

Table 3
Position, height, distance and the year of exposure of the roots in reach B

Site number	Root number and piece of root number		Exposed root length (m)	Root orientation	Height above the riverbed (m)	Distance from cutting surface (m)	Most probable year of exposure
BVI	13	a	0.7	Oblique	1.7–2.2	0.4	1982
		b				0.3	1983
		c				0.4	1983
	14	a	0.8	Oblique	1.5–1.9	0.2	1973–75
		b				0.6	1974
		c				0.3	1977
	15	a	0.4	Horizontal	2	0.2	1977
		b				0.3	1997–79
	16	a	0.8	Horizontal	2	0.3	1983–85
		b				0.6	1978
		c				0.4	1977
BVII	17	a	1.4	Horizontal	2.1	0.25	1982
		b				0.1	1997
		c				0.3	1997
		d				0.15	1997
	18	a	1	Horizontal	2.1	0.4	1974
		b				0.6	1973–75
		c				0.15	1977
	19	a	0.6	Oblique	1.8–2.1	0.4	1983
		b				0.3	1991
		c				0.45	1997
	20	a	0.5	Oblique	2.6–2.8	0.2	1980–84
		b				0.35	1986
		c				0.2	1993–94
	21	a	0.4	Vertical	2.3–2.7	0.1	1980–82
		b				0.3	1977–79
		c				0.4	1983
	22	a	0.25	Oblique	2.6–2.7	0.05	1997
		b				0.05	1997
	23	a	0.9	Horizontal	2.7	0.45	1990–92
		b				0.3	1977–79
		c				0.3	1983
		d				0.4	1973–74

treeless sections located in reach A, numerous rock outcrops occur within the banks and the banks without trees are not wider than the banks covered with trees. This indicates that intensive erosion did not take place in these sections. Most often, the treeless sections in the Bílá Opava valley in reach B are significantly wider than the forested sections. The banks in reach B are composed mostly of erodible gravels. The probability is substantial that the trees that grew on the banks were undercut and transported downstream.

Living roots with ends still growing in the soil are particularly useful for bank erosion dating because after exposure these roots usually form wide rings with clearly visible anatomical changes. More than half the roots sampled in the Bílá Opava valley floor formed clear rings after exposure. Sometimes roots are damaged during exposure occurring during erosion. While these roots produce suppressed rings after exposure, most often the anatomical changes are clear. This form of growth was observed in 14 root samples in the Bílá Opava valley floor. Alestalo (1971) and Shroder (1980) described suppression occurring after root exposure.

If roots are exposed at one site in different horizons or strata of bank sediments, it is important to sample all of them to identify the possibility of occurrence of more erosive events in one riverbed/valley cross-section. Samples of the thickest roots should be collected from the same horizon, as these roots are potentially the oldest and have recorded a relatively large number of erosion episodes.

Samples should be taken at a distance of 10 cm from one another. This precise sampling enables the capture of gradual exposure as occurs when the root is exposed in sections during floods. Thus, one exposed root may document several erosion episodes. As a result of gradual exposure, root fragments sampled from the soil neighbouring the direction of exposure are younger and younger. Gradual exposure was identified in 20 of 23 sampled roots in the Bílá Opava valley (Tables 2 and 3). Only three roots (1, 12 and 22) were exposed in the July 1997 flood alone.

Sometimes, gradually exposed roots feature an illegible record of the years in which exposure occurred within one sample (Fig. 5b). The 2–5 rings that follow root exposure record gradual anatomical changes. At first, the rings recording exposure are wider than previously, though often the division between early and late wood is very weakly visible. The next rings record more and more visible anatomical changes. Hence, in the case of such root samples, it is only possible to estimate their exposure time with a precision of up to several years. The first of the tree rings recording anatomical changes is to be considered as the moment when root fragment exposure began. While it is possible that the same anatomical changes from gradual exposure could occur in soil, more experimental study is needed on tree ring formation in relation to gradual exposure.

Gradual exposure in the root samples collected in Bílá Opava valley occurred especially in case of roots exposed in reach B where the erodible alluvium banks occur (root samples 14a, 15b, 16a, 18b, 20a,c, 21a,b, 23a,b,d). This form of root growth commonly testifies to less intensive bank erosion events. For example, root sample (11b) was exposed gradually, thus the change in wood anatomy also occurred gradually (Fig. 5b). On the other hand, root (1b) from site I was dramatically exposed in 1997, which is reflected in the sudden change in its wood anatomy (Fig. 5a).

Apart from anatomical changes in roots that occur immediately after their exposure, changes also frequently occur after longer periods of exposure, consisting of a dramatic decrease in tree-ring size, often accompanied by an accumulation of resin ducts as in case of root 20b (Fig. 5c). At least two suppressed tree rings (more than 50% thinner than previous rings) occurring after a longer period of exposure were observed in 17 roots fragments sampled in the Bílá Opava valley. Such changes are often the result of damage to the exposed roots by the transported material. They may also be the result of exposure of the end of the root, which causes root necrosis. In order to date such roots, their structure must be analyzed under a microscope.

The oldest spruces growing in the Bílá Opava River valley are up to 110 years old. The exposed roots are most commonly much younger, which limits conclusions on bank erosion to about the previous 100 years.

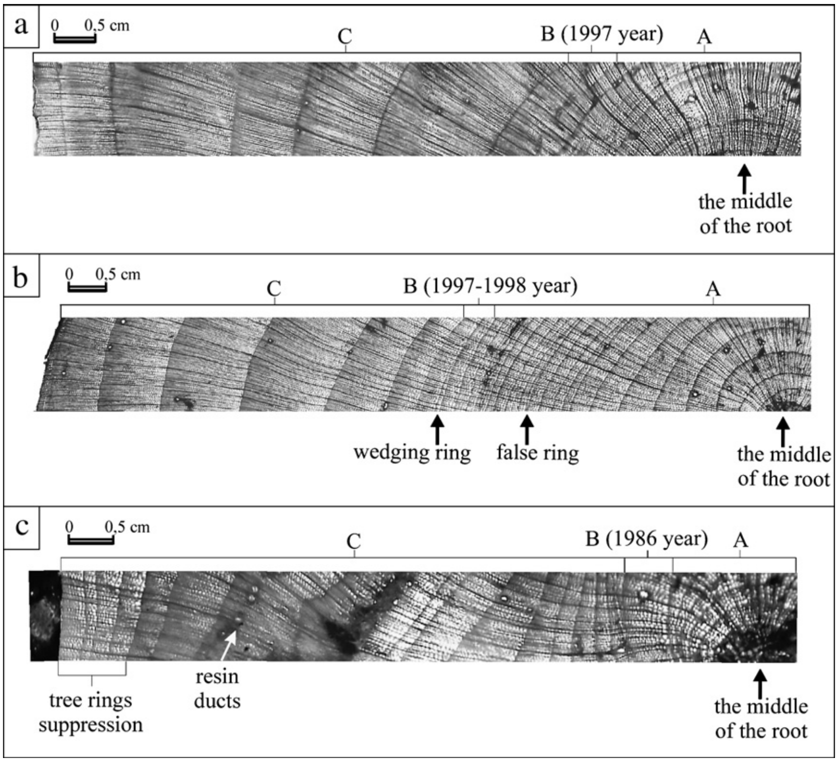

Fig. 5. Microphotograph showing part of root sample cross-sections with anatomical changes, (a) tree rings formed before exposure, (b) first year with anatomical changes (tree ring formed simultaneously with exposure), (c) tree rings formed after exposure.

Roots testifying to bank erosion can be broken by the transported material. Trees with exposed root systems are often undercut and fall into the riverbed. Therefore, the quantity of exposed roots testifying to floods in the earlier years of this period is rather small, while later erosion episodes are well recorded in the wood of exposed roots. Hence, the large majority of roots exposed in the Bílá Opava valley floor document bank erosion episodes from the last 40 years.

False rings, missing rings or wedging rings occur in stems in a similar manner as in roots (Schweingruber, 1988). They may distort the number of years that have elapsed since the erosion episode. However, errors relating to that limitation are not large, since, in contrast to cores collected from trees, the whole cross-section is examined in the case of roots. This makes identification of false, missing or discontinuous rings easier. Tree rings formed in roots after exposure are similar to the rings produced in stems, meaning that root form growth after exposure is very clear. Before exposure lots of wedging, as well as false and probably missing rings in roots occur (Fig. 5b). Cross-dating can potentially eliminate false and missing rings within the roots. The authors attempted to cross-date roots samples, but the relatively short tree ring series occurring after exposure and the numerous growth disturbances such as the dramatic decrease occurring after longer periods of exposure and a long series of compression wood made it impossible to reach conclusions. Perhaps cross-dating root ring series with stem ring series would be more accurate. Before cross-dating, site/local chronology should be reconstructed to eliminate as much error as possible because of missing and false rings that may occur within the stems.

Compression wood occurs within numerous root cross-sections; in 21 root samples compression wood occurs in the first ring after exposure. In about 38 cases, compression wood occurs after a longer period of exposure. This suggests that compression wood is not a precise marker for establishing when erosion events took place.

The time of root exposure as identified from the analysis of anatomical changes within its tree rings is not always the same as the actual year of exposure of that root. Tree rings are formed in a temperate climate in the period from May to November (Zielski and Kr1piec, 2004). When a root is exposed at this time, anatomical changes are visible in the area of a tree ring. If the root exposure occurred from January to May, the tree ring may be changed in the same year as the exposure occurred. If the exposure occurred between November and December, the tree ring with anatomical changes will appear the following year. A marker of exposure may be thus recorded in roots 1 year after an erosion episode.

The authors decided not to calculate bank erosion rates, which depends on a rather precise time that the erosion rate is measured. The recording of erosion is more precise when more recent events are analyzed. This means that is not possible to select a representative period for measuring erosion rates in the Bílá Opava valley and the results of such calculations could be distorted.

4.2. Bank erosion of the Bílá Opava River in reach A

The root exposure analysis shows that bank erosion took place in reach A of the Bílá Opava valley during the last 100 years (Fig. 6). The earliest recorded bank erosion episodes occurred in 1912, 1931 and 1949. Later erosion periods were concentrated in the years 1956–1967, 1988–1995 and 1997. The best recorded erosion episode is the one in 1997, when as many as 12 of the 28 root fragments were exposed.

The earliest registered bank erosion episodes were recorded in site II (1912) and site III (1931 and 1949). At site II, exposed spruce roots are growing as much as 2.4 m above the level of the riverbed. One can suspect that only extreme precipitation episodes would cause flows permitting the hillslope to be undercut at such a level. The date of root exposure of this spruce in 1912 corresponds to the floods of 1913 and 1914. During the latter, in Mikulowice 20 km to the north, 128 mm of precipitation was recorded during 1 day in 1913 year (Polách and Gába, 1998). Partial exposure of root 6 at site III may be related to the intense precipitation that occurred in the area of the Hrubý Jeseník in 1930 or 1931. The root at site III was exposed in 1949. The root documents bank erosion which occurred during intense precipitation in 1948, when 126 mm of rain was recorded at Praded massif.

A large group of root fragments exposed at sites I–IV in reach A in the period between 1956 and 1967 are a result of bank erosion during two floods which took place in the Jeseniki mountains in 1958 and 1966. The earlier resulted from rainstorms registered in Jeseniki, as it is known that the Desná River flooded then (Polách and Gába, 1998). The analysis of root exposure shows that precipitation also covered the Bílá Opava valley, where bank erosion took place. At that time the bank at site II was eroded, which would demonstrate a considerable flow during that flood. Also, fragments of roots 6 and 7 at site III were exposed, as well as root 10 at site IV. In 1966, a large flood covered the area around

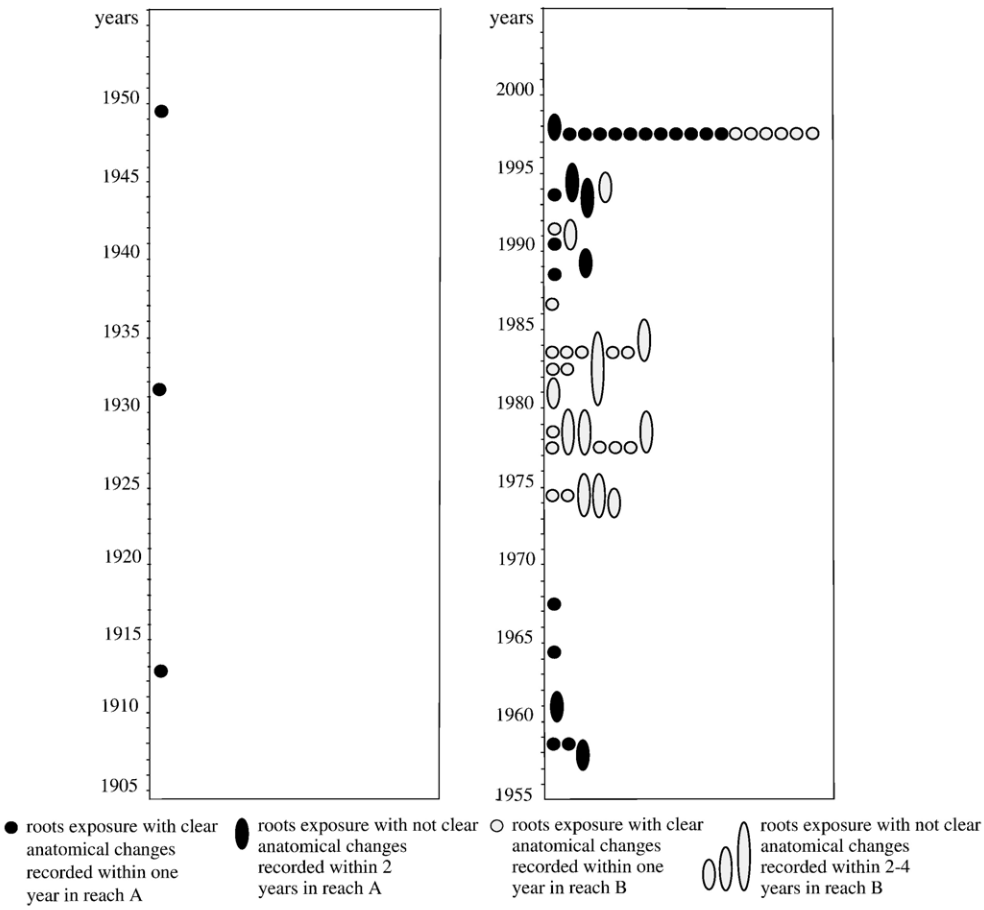

Fig. 6. Years of tree roots exposure in the Bílá Opava riverbed.

the Jesenik massif (Polách and Gába, 1998). The flood in the Bílá Opava riverbed caused erosion at site II, where a fragment of root 2 was exposed.

The group of root fragments exposed in the years 1988–1995 covers the period in which both historical and hydrological sources give no information about significant floods/rainstorms in the Jeseniki area. At this time fragments of root 8 were exposed at site III, root 9 at site IV and root 11 at site V. Perhaps erosion in this period occurred as a result of rapid precipitation that was so short that it was not registered at the Karlowice gauge. However, in such a case roots would inform us about a rapid erosion episode, while 4 out of 7 roots were exposed gradually.

Root exposure in the years 1988–1995 may be a result of local changes in the riverbed morphology. Bank erosion may be started by redeposition of boulders, the transport of which is testified to by imbrication in the Bílá Opava riverbed. The boulders are usually transported short distances (Baker and Ritter, 1975, Pizzuto et al., 1999), producing erosion by local redirection of the current towards the banks, which have not suffered erosive activities before. Such a situation occurs in the case of roots exposed at site IV, where boulders which accumulated in the upper zone direct the current towards the left bank where erosion occurs. Systematic washing out of the left bank resulting from the change in the riverbed configuration may help bank erosion that takes place regardless of high water episodes. This is confirmed by gradual exposure of as many as three root pieces at this site. A similar situation was observed at site V, where boulders deposited in the centre of the riverbed divide the current into two parts. The left part intensively undercuts the bank as a result of bank erosion occurring in the years 1988–89.

Changes in the riverbed morphology may be caused by hillslope material supply. The supply zone, to which the river is predisposed due to the steeply sloping valley sides, occurs in the valley studied above sites III and IV. There is evidence for this in visible debris tracks on the hillslope. In the Jeseniki, debris flows occur periodically. Recently they occurred in the Keprník Massif, 10 km to the north west, where in the summer of 1991 two large debris flows, and at least several smaller ones, were produced (Gába, 1992). It is most likely that the material had recently been loosened above the sites under study, which is testified to by the large amount of angular material deposited in the Bílá Opava riverbed. The change of riverbed morphology related to material supply to the riverbed could produce changes in the flow direction. As a result, bank erosion started to take place in new locations and erosion occurred even with relatively small discharge.

Erosion of the banks may be enhanced by debris dams formed of CWD positioned perpendicular to the river axis (Gregory et al., 1985; Gurnell et al., 2000). Debris dams may change the flow direction during floods (Marston, 1982; Robinson and Beschta, 1990), in particular in the riverbeds of mountain streams. In such cases, overflow channels even form in the valley floor (Kaczka, 1999). It is possible that bank erosion at sites III–V of the Bílá Opava riverbed in the years 1988–1995 was produced by debris dams that were destroyed during a later flood in 1997. This is all the more likely because in the reach where the sites are located many dams are caught by trees and boulders and deposited transverse to the river direction. It seems that a width of valley floor similar to CWD length (about 20 m) is a decisive factor in promoting intensive CWD deposition on this reach. One such debris dam is situated 5 m below the roots exposed at site V.

Significant transformations of riverbed morphology were observed in the areas affected by precipitation in July 1997 (Zieliński, 2003). Large undercuts of banks, slopes and terrace levels were formed at that time (Owczarek, 2004a,b). Water in the upper reach of the Bílá Opava valley floor flowed in a narrow riverbed during the flood of July 1997, which probably enhanced bank erosion. This occurred here at sites I, III and V. At site I, 3 out of 4 root fragments studied were exposed, while at site V as many as 4 out of 5 fragments were so affected. All three roots studied at site III were partially exposed during the flood of 1997.

Due to a relatively large number of roots affected, bank erosion at site III can be interpreted separately. It occurred in the years 1931, 1949, 1958, 1993 and 1997. Such a big difference of time between the exposure of particular parts of the roots testifies to lateral stability of the riverbed at this site. Bank erosion may occur here only during big floods. This is demonstrated by the possible correlation of all erosion episodes which took place at site III, except for 1993, with large floods.

4.3. Bank erosion of the Bílá Opava River in reach B

In reach B, signals of bank erosion have only appeared since 1973 (Fig. 6). At this reach, due to greater intensification of water flow and alluvial banks, the probability of bank erosion is greater than in the upper, rocky reach A of the river. Therefore, trees growing in the lower reach, which feature older erosion episodes in their exposed roots, are felled to the river, which is testified by a high number of CWD deposited in the riverbed in reach B. Lack of older signals of bank erosion in the lower reach should be interpreted as a symptom of the high rate of bank erosion in reach B.

The majority of root exposure episodes in reach B are found within two periods of time, the years 1973–1983 and 1986–1995. Most root exposure episodes, including several episodes a year, were recorded in 1977, 1983 and 1997. It is hard to define the floods responsible for bank erosion in the years 1973–1983 precisely. As many as 9 out of 23 root fragments recorded gradual exposure. Moreover, signals of root exposure are scattered across the period analyzed. Bank erosion of the Bílá Opava could be enhanced by rainstorms in late August 1972, when Praded gauge recorded 83.7 mm of rain (Polách and Gába, 1998). Bank erosion in reach B can also be the result of heavy precipitation which occurred in 1977 in a significant part of Europe, including the Šumperk and Jeseník districts. At that time intensive bank erosion took place at site VI, where three out of four roots analyzed were exposed.

As many as 7 out of 23 root fragments from the period analyzed were exposed in 1983, although no precipitation data document such an erosion episode. The reason for root exposure during several years following floods may be the high erodibility of previously exposed alluvial sediments. Undercuts formed during high floods are susceptible to erosion, which makes relatively small floods occurring after the much bigger ones cause erosion. Gradually the erosional undercut is stabilized by the flora, which limits erosion. The high erodibility of sediments exposed in the lower part of the valley floor is testified by frequent root exposure periods at particular sites. Almost all roots at sites VI and VII were exposed with a frequency of several years, while roots in the upper, rocky reach are exposed with a frequency of several dozen years (Fig. 7).

What is characteristic is the fact that in the period between 1973 and 1983 roots were only exposed in reach B. This may mean that precipitation episodes responsible for bank erosion did not cover the upper part of the valley. It is more probable, however, that precipitation was not heavy enough to erode the rocky banks

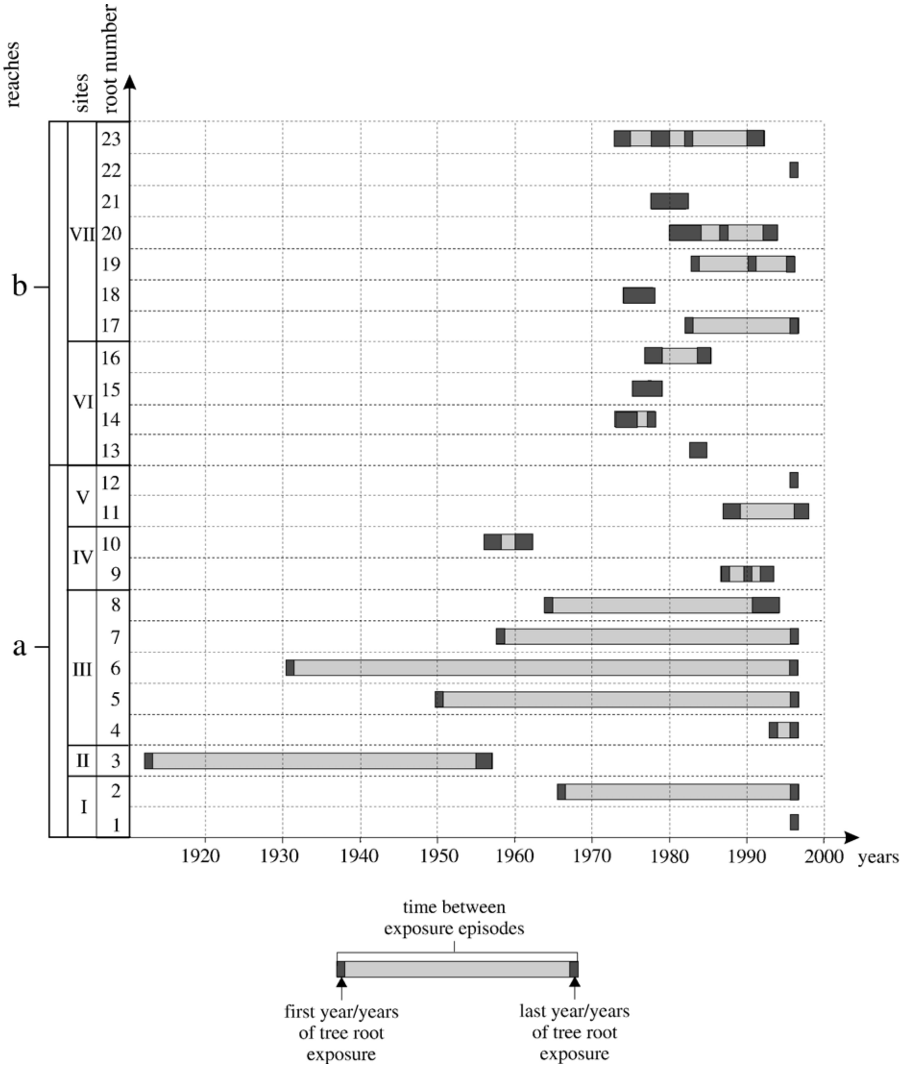

Fig. 7. Time and frequency of tree root exposure in the Bílá Opava riverbed.

in reach A, yet was sufficient to undercut terrace levels in reach B.

The period of bank erosion, registered in the lower reach in the years 1986–1994, also occurred in reach A. Bank erosion was also recorded by three roots at site VII. Signals about root exposure are gradual here, which suggests several episodes of erosion. Similarly as in reach A, in the lower part of the reach, erosion in the years 1987–1985 could have been caused by debris dams that appear periodically. Dams may also cause water flow in the terrace levels zone where even slight but systematic floods result in erosion.

Dating of root exposure shows that during the flood of 1997 erosion in the lower reach was insignificant. Exposure only referred to roots 15, 17 and 19 of the spruce growing at the edge of the terrace level of 2.8 m at site VII. It should be noted, however, that trees growing on lower banks were felled onto the riverbed during the extraordinary flood in 1997.

The results of dating of root exposure of spruce growing on the edge of terrace levels at site VII allow for analysis of bank erosion in the cross-section of the valley floor. It started in the years 1973–74 within the upper terrace at 2.8 m. In the years 1977–1979, 1982–1988, and 1991–1994, bank erosion occurred several times in both the lower and the upper terraces. It also took place in the upper terrace in 1997. The significant bank erosion in the terrace levels that are situated high above the riverbed is a result of the heavy flood of 1977. Since then, erosion has very often occurred in the area of both terrace levels. During the flood already mentioned, a debris dam was probably formed, which during the next small floods made water flow into the area of the terrace levels, undercutting them. Presently, there is a small debris dam above exposed roots, yet it is not significantly obstructing water flow and simultaneously undercutting the upper terrace levels. It seems that the debris dam producing erosion at the site studied was destroyed during the flood of 1997. Since then undercuts around the terrace levels have become inactive.

5. Conclusions

This study has shown that a number of factors need to be taken into account when carrying out a dendrogeomorphological assessment of riverbank erosion history. In particular, the sampling of roots representing different heights above the riverbed is needed because this will capture the recording of different erosion episodes. Samples should be taken from the thickest root along the same strata; these roots are potentially the oldest and have recorded a relatively large number of erosion events. Sub-samples should be taken at 10-cm intervals, such a precise sampling can reveal gradual exposure. One problem with the methodological approach is that false rings, missing rings or wedging may distort the number of years that have elapsed since the erosion episode. Cross-dating can potentially eliminate false and missing rings within the roots, however, in this study relatively short tree-ring series occurring after exposure and numerous growth disturbances such as a long series of compression wood precluded its application. Future research should focus on cross-dating root ring series with stem ring series to improve accuracy.

The main conclusions regarding the bank erosion history of the Bílá Opava River are the following:

- Root exposure analysis showed that one can distinguish four bank erosion periods: the oldest root exposure signals are significantly dispersed over the period 1912–1967, and later signals are less dispersed within two periods, 1973–1984 and 1986–1995, with the most numerous group of signals in 1997.
- Bank erosion related to root exposure episodes in the first half of the 20th century was only recorded in reach A of the Bílá Opava River. Only three bank erosion episodes were observed here in the years 1912, 1931 and 1949, corresponding to heavy floods documented in historical sources. These episodes must have been significant enough for bank erosion to become active in the rocky riverbed. Simple erosion signals in the upper part of the valley studied took place in the years 1956–1967. Perhaps they are related to two heavy floods that occurred in Jeseniki in 1958 and 1966.
- In the period between 1973 and 1984, roots were only exposed in reach B. Bank erosion occurred gradually here, which is demonstrated by the overlapping of several erosion episodes, the first of which triggered sediment exposure. Perhaps this was encouraged by the floods of 1972 and/or 1977. In the period 1973–1984 bank erosion was affected by the riverbed morphology at particular sites. Situations have been defined where the location of boulders enforces local bank erosion. Therefore, it is not necessarily heavy precipitation that causes erosion, it may occur after a change of bed configuration. Then water systematically undercuts the bank even during relatively small floods.
- In the period 1986–1994, banks eroded in reaches A and B. Historical sources or meteorological data do not confirm heavy precipitation/floods in the area of the Jeseniki. Roots were most frequently exposed gradually, which would suggest systematic bank undercutting. Erosion in reach A could be caused by changes of the riverbed configuration of the Bílá Opava, influenced by hillslope material supply from the slope, which was particularly intensive in the Jeseniki in 1991. Bank erosion in reach B could also have been caused by the formation of debris dams and the undercutting the terrace levels.
- Bank erosion of the Bílá Opava was most intensive during the flood of 1997. At the time rocky banks were undercut at four out of five sites in reach A. Root exposure analysis shows that during the flood of 1997 erosion in the lower part of the valley in reach B was not as intensive as in the upper part. However, here undercutting referred to the erodible sediments of terrace levels, which must have intensified the erosion. Perhaps some trees were felled and transported downstream, which is testified to by the many CWD in the lower part of the river.

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