Chapter 13
The May 2010 Landslide Event in the Eastern Czech Republic

Tomáš Pánek, Veronika Smolková, Karel Šilhán, and Jan Hradecký

Abstract In May 2010 intensive rainfalls and consequent floods affected Central Europe, including the eastern part of the Czech Republic. In the period 15–25 May 2010, more than 150 landslides originated in the Outer Western Carpathians and their foredeep. In the case of the Girová rockslide, the May 2010 rainfall event only supplied the final triggering push. The main preconditions of slope failure were long-term, internal changes within the rock mass. As evidenced by dendrogeomorphological dating, rock strength weakening was connected to long-term (decennial-scale) creep leading to the final catastrophic movement. Many trees from the upper section of the landslide do not reveal any year of reaction wood. It could be explained by a translational, blocklike character of movement.

Keywords Rockslide • Translational landslide • Dendrogeomorphology • Radio-carbon dating • Reaction wood analysis • Czech Republic

13.1 Introduction

Due to specific lithological and structural conditions, landslides repeatedly activate in the Outer Western Carpathians (OWC), usually triggered by meteorological events: intensive and/or long-lasting rainfalls in combination with snowmelt. From last decades, the most significant (and well-documented) events in the eastern part of the Czech Republic were the 1997 and 2006 landslide activations (Rybář and Stemberk 2000; Krejčí et al. 2002; Bíl and Müller 2008; Klimeš et al. 2009). In July 1997, 257 mm of precipitation fell within 5 days in the study area (Kirchner 2001).

T. Pánek • V. Smolková • K. Šilhán • J. Hradecký (✉)
Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Chittussiho 10, 71000 Ostrava, Czech Republic
e-mail: tomas.panek@osu.cz; veronika.smolkova@osu.cz; karel.silhan@osu.cz; Jan.Hradecky@osu.cz

More than 1,500 landslides of different types originated causing extensive damage
(€31 million) to buildings and infrastructure (Krejčí et al. 2002). At the turn of
March and April 2006, rapid snowmelt and intense precipitation triggered and
reactivated more than 80 (mostly shallow) landslides in the study area (Bíl and
Müller 2008). During both events, a notable share of the active landslides were
associated with previous slope failures.

In May 2010, intensive rainfalls and consequent floods affected Central Europe,
including eastern part of the Czech Republic. During the period 15–25 May 2010,
more than 150 landslides originated in the Outer Western Carpathians and their
foredeep (Fig. 13.1a), which brought significant economic losses (damage to
houses, infrastructure, and forests) (see also Chap. 2, Gorczyca et al. in this
volume). The financial costs of mitigation works exceeded €5 million.

In this chapter, we describe the May 2010 landslide through (1) the distribution
of landslides in relation to rainfall patterns, (2) the delineation of the spatial
relationships between activated landslides, geological settings, and antecedent
landslides, and (3) the demonstration of the most pronounced slope failure
reactivated during the May 2010 event.

13.2 Regional and Hydrometeorological Settings

Most of the landslides are concentrated in the OWC and their foredeep (Fig. 13.1).
The area is built of Cretaceous–Oligocene flysch bedrock thrust onto the
Subsilesian, Silesian, and Magura Nappes of NW vergency during the Miocene
(Menčík et al. 1983). Predominantly thick-bedded flysch complexes prevail in
the southern Silesian Nappe and within the Magura Nappe and form the highest
parts of the Beskydy region (1,323 m). Weaker thin-bedded flysch complexes of
the northern part of the Silesian and Subsilesian Nappes form a rather subdued
hilly landscape covered by Neogene and Quaternary deposits in the western and
northern sections of the region (Fig. 13.1a). Mean annual precipitation totals (for
1961–2000) in the study area range from ca. 650 mm in lower-lying areas to more
than 1,200 mm at the highest elevations (Tolasz et al. 2007).

Extremely high precipitations were recorded in the northeastern part of the
Czech OWC on 16–18 May 2010 (Fig. 13.2). Shallow subsurface saturation can
be documented by the antecedent precipitation index (API_{30}), the precipitation
totals for the previous 30 days:

$$API_{30}(d) = \sum S_n \cdot 0.93^n,$$

where S_n (mm) stands for daily precipitation totals of n days ($n = 1, 2, \ldots, 30$)
before the day d and 0.93 is the evaporation constant (Hladný 1962). For the study
region and for 16 May, higher than 100 mm was calculated (Fig. 13.2a): in the
mountain areas 20–30 mm fell on 15 May, and, in the following 2 days, even much
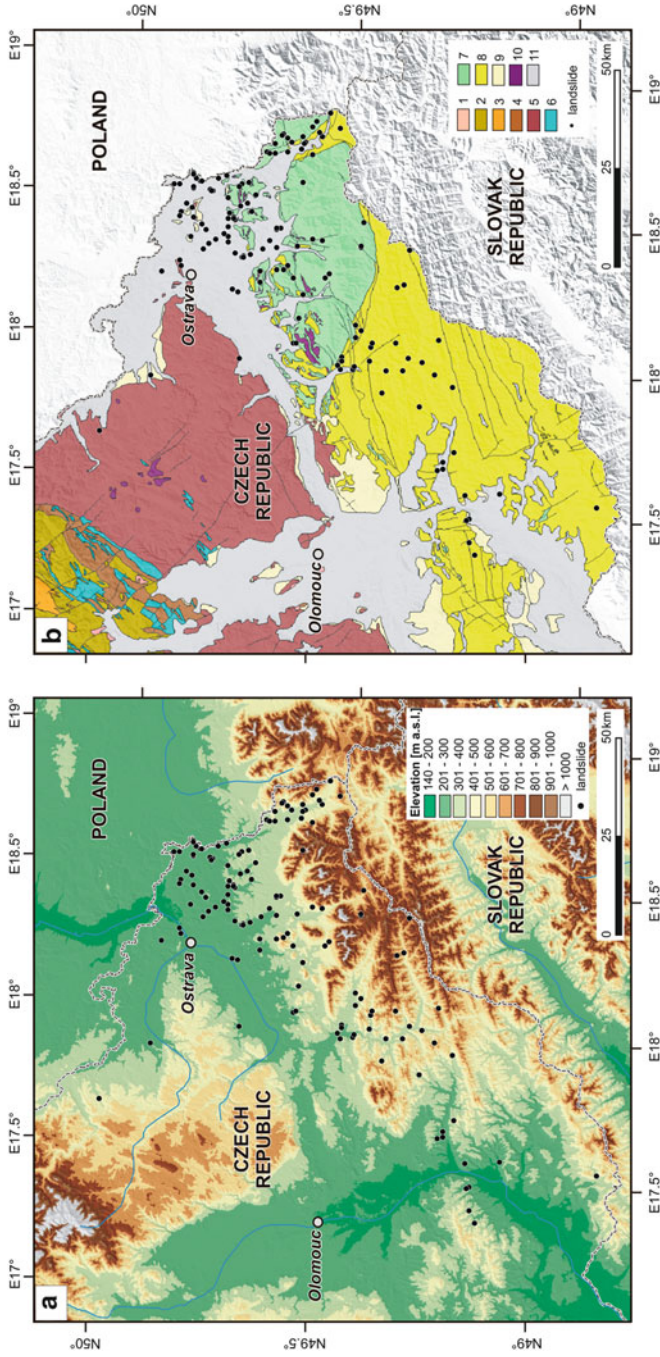
Fig. 13.1 Location of the study area and spatial distribution of the May 2010 landslides in the eastern part of the *Czech Republic*. (**a**) Distribution of the landslides in the context of topography and hypsometrical conditions (Source of elevation data: SRTM3v2). (**b**) Geological setting: *1–6*, Proterozoic–Mesozoic rocks of the Bohemian Massif; *7*, Mesozoic flysch deformed by the Alpine orogeny; *8*, Tertiary flysch deformed by the Alpine orogeny; *9*, Tertiary unconsolidated deposits; *10*, Tertiary volcanic rocks; *11*, Quaternary unconsolidated deposits. (Reprinted with kind permission from Springer Science+Business Media: Landslides, Rainfall-induced landslide event of May 2010 in the eastern part of the Czech Republic, 8, 2011, 507–516, Pánek T et al.)
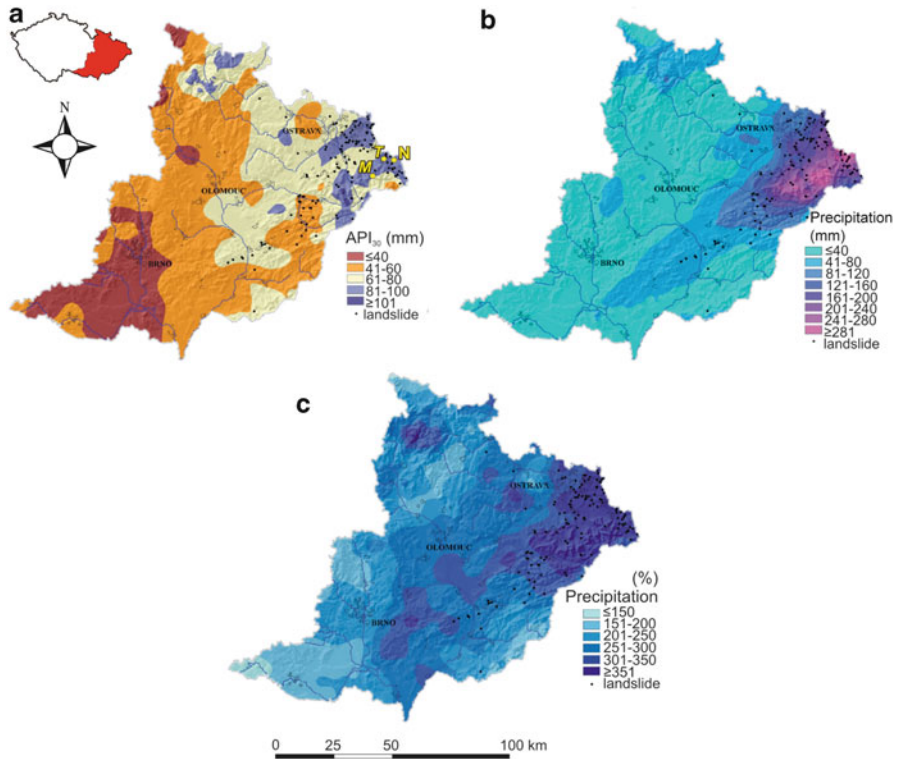
Fig. 13.2 Spatial distribution of precipitation in the eastern Czech Republic in May 2010 (meteorological stations: *M* Morávka dam, *T* Třinec, *N* Nýdek). (**a**) Antecedent Precipitation Index API_{30} (mm) for 16 May. (**b**) Precipitation totals (mm) on 16–18 May. (**c**) Precipitations of May 2010 as percentage of the 1961–2000 mean May precipitation (Reprinted with kind permission from Springer Science+Business Media: Landslides, Rainfall-induced landslide event of May 2010 in the eastern part of the Czech Republic, 8, 2011, 507–516, Pánek T et al.)

higher values were recorded in the Beskydy Mountains and in the adjacent areas. On 16 May, daily totals above 100 mm were recorded at 33 stations of the Czech Hydrometeorological Institute (maximum in Třinec, at 340 m elevation, 179.8 mm). On the following day, 17 May, only 5 stations recorded more than 100 mm (Morávka dam, 500 m, 115.0 mm), but at 37 other stations more than 50 mm was measured. On 18 May, only 4 stations recorded more than 60 mm (Nýdek, 400 m, 71.0 mm), and 17 stations measured ≥30.0 mm. Three-day precipitation totals (16–18 May) made up more than 300 mm at six stations (at Třinec, 327.6 mm) and more than 250 mm at five stations in the study area (Fig. 13.2b). Thus, precipitation totals for May were in many locations more than three times higher than the corresponding monthly means for 1961–2000 (Fig. 13.2c). Extreme daily precipitations induced not only extensive landslides but also floods: peak river flows corresponded to discharges of 50–100 years return period.

13.3 Methods

Slope deformations activated in May 2010 were studied by field *geomorphological survey*: extraction of geological and topographical information from topographical (10 m-resolution DEM) and geological sources (Menčík et al. 1983) using GIS to reveal the spatial distribution of all activated landslides. The dimensions of 134 landslides were measured directly in the field. The 150 landslides reported to local authorities can only be considered a minimum number. This dataset was enlarged by an aerial survey performed in the Beskydy Mountains at the beginning of July 2010.

The largest studied landslide (Girová) was mapped by GPS in detail (Pánek et al. 2011a, b). Inaccessible corners and overall context of this slope deformation were studied on *aerial photos*. Radiocarbon and dendrogeomorphological dating was used to study the chronological evolution of mass movements within the area of the Girová landslide. Conventional and AMS *radiocarbon* (^{14}C) *dating* was provided by the Beta Analytics (Miami, USA) and Gliwice Radiocarbon Laboratory of the Institute of Physics, Silesian University of Technology (Poland). Historical chronology of landslide movements for the past few decades was derived using *dendrogeomorphological dating*. The analysis was performed using 152 increment cores coming from 76 individuals of common spruce (*Picea abies*). All inclined trees that did not fall during the May 2010 catastrophic failure were sampled (56 trees; 112 increment cores); other samples were taken from 20 undisturbed trees (40 increment cores) growing completely outside the landslide area for reference. Two increment cores were taken from each sampled tree using Pressler increment borer (one on the upper side and the other one on the lower site of the trunk) (Stoffel and Bollschweiler 2008). All samples were cross-dated with reference chronology in order to identify and correct false/missing rings. Historical events were dated through the identification of the first years of reaction (compression) wood occurrence (i.e., growth reactions of conifers to tilting). Results of the *reaction wood analysis* are presented by the *It index* expressing the percentage of trees containing geomorphic signal (reaction wood) from all sampled trees alive in year *t* (Shroder 1978).

13.4 The May 2010 Landslide Events

The first landslides happened on 15 May, whereas the last of them were reported on 25 May 2010. The majority of movements started on 18 May just after the most intensive 3-day rainfall episode (Fig. 13.2). The event was accompanied by numerous small failures, 88% of which reached 10^4 m^2 area (Fig. 13.3) and only 12% of the measured landslides affected areas larger than 1 ha. The size range of observed landslides is dominated by the giant Girová landslide with 20 ha area and ca. 2–3 million m^3 volume. Most slope failures were *incipient landslides* (mainly in the
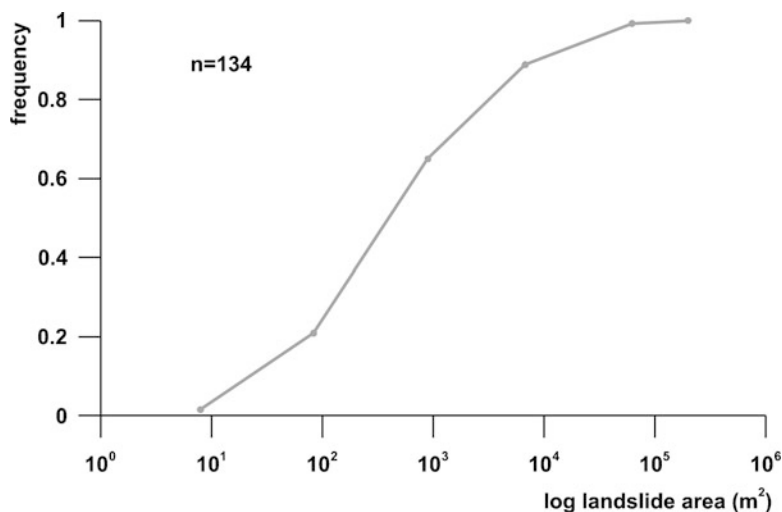
Fig. 13.3 Cumulative size frequency distribution of the May 2010 landslides in the eastern Czech Republic ($n = 134$ landslides with measured area). (Reprinted with kind permission from Springer Science+Business Media: Landslides, Rainfall-induced landslide event of May 2010 in the eastern part of the Czech Republic, 8, 2011, 507–516, Pánek T et al.)

stage of tension cracks), *shallow translational debris slides*, and *soil slips* (Fig. 13.4). Except for the isolated case of the Mt. Girová deep-seated rockslide, slope failures showed shear surfaces at medium (10–30 m) to shallow (less than 10 m) depths.

Most of the 150 reported landslides (67%) affected unconsolidated Quaternary colluvial, fluvial, aeolian, and glacial deposits. Thin-bedded flysch bedrock characterized by the dominance of clay stones/mudstones was involved in 16% of the cases (Fig. 13.5a). Most of the instabilities (67%) occurred in hilly (local relief up to 100 m), urbanized, or agricultural landscapes. They are mainly clustered on steep slopes ($>25°$) undercut by stream erosion (Fig. 13.5b, d). A very important aspect of the May 2010 landslide event was that 70% of instabilities developed on older (Holocene or historic) landslide terrains (Fig. 13.5c). Some of these landslides have experienced *multiple activation* over the past few decades (e.g., in 1972, 1995, 1997, 2005, and 2006; see, e.g., Krejčí et al. 2002; Hradecký and Pánek 2008; Pánek et al. 2009).

There is a quite *uniform spatial distribution* of the studied landslides in areas with different precipitation totals (16–18 May 2010, Fig. 13.2b), which were their main trigger. Four precipitation intervals (81–120, 121–160, 161–200, and 201–240 mm) involve 19, 15, 19, and 18% of all investigated landslides, respectively. On the other hand, 65% of the recorded landslides are limited to areas where May totals are more than three times higher than the monthly mean for 1961–2000 (Fig. 13.2c). Moreover, 50% of the landslides are situated in the region with API_{30} between 80 and 100 mm (Fig. 13.2a). The relative absence of landslides in the highest parts of the Beskydy Mountains (despite highest precipitations) is most likely explained by rather rigid sandstone-dominated flysch and dense forest cover.

Fig. 13.4 Examples of typical landslides of the May 2010 event. (**a**) Right bank of the Horní Datyňka River is affected by translational landslides along a length of 100 m due to lateral erosion (Horní Datyně village). (**b**) A debris slide situated below the church in Skalice village formed due to lateral erosion of the Morávka River. (**c**) Incipient translational landslide in Orlová town. (**d**) Tension cracks in the upper part of a shallow translational landslide, Horní Bludovice village. (**e**) Rotational landslide in the Quaternary deposits, endangering two houses in Stonava village. (**f**) Large rotational landslide in Doubrava village. Two houses suffered structural damage and had to be demolished (Photos by L. Kubiszová)

13.5   Case Study: The Girová Landslide

The largest catastrophic landslide (area, ca. 20 ha; length, 1,150 m; volume, 2–3 million m^3) associated with the May 2010 rainfall event affected the southern slope of Girová Mountain (839 m) in the vicinity of Jablunkov town (Pánek et al. 2011a, b). It is the largest long-runout landslide in the Czech Republic over the past few decades. The landslide destroyed ca. 18 ha of forests and caused economic losses exceeding €0.5 million.

The whole SW slope of the Girová Mountain is occupied by a *complex slope deformation* (sensu Dikau et al. 1996) of dimensions of 1.5 × 1.0 km. The geomorphological mapping performed in the western part of the slope deformation in
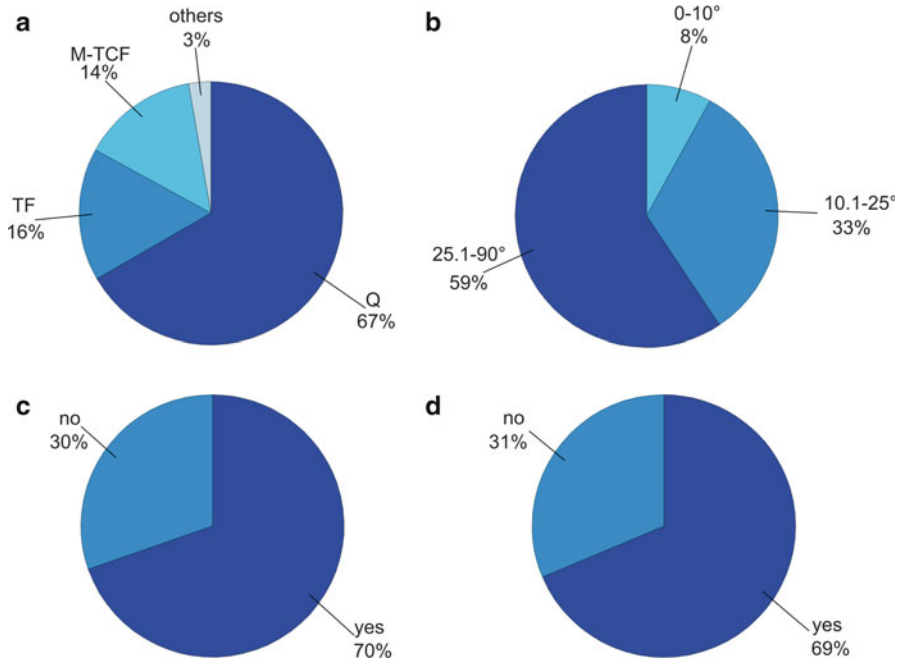
Fig. 13.5 Selected properties of the May 2010 landslide event ($n = 150$). (**a**) Landslide distribution in different lithological units (*Q* Quaternary deposits, *TF* thin-bedded flysch, *M-TCF* medium to thick-bedded flysch). (**b**) Landslide distribution within hillslope gradient classes. (**c**) Percentage of landslides that originated within old landslide terrains. (**d**) Percentage of landslides situated on slopes actively undercut by stream erosion. (Reprinted with kind permission from Springer Science+Business Media: Landslides, Rainfall-induced landslide event of May 2010 in the eastern part of the Czech Republic, 8, 2011, 507–516, Pánek T et al.)

2005 revealed a trough-like source area with 10 m high, soil-mantled, head scarps, peat bogs and the extremely long (1,500 m), eroded accumulation lobe of an ancient long-runout landslide (Fig. 13.6). Due to regression, this slope segment collapsed again in the night from 18 to 19 May 2010 and formed a wedge-like, *translational rockslide*. The movement started just below the mountain ridge and affected deeply weathered clay stone/mudstone flysch of the Magura Unit in the intersection zone of two normal faults dipping 250°/50° and 110°/55°, respectively. The translational displacement of this deep-seated block significantly destabilized the slope by (1) unloading the remaining mass upslope – particularly in the western part of the head scarp – and by (2) overloading the central part of the slope. Subsequent collapse of the frontal part of the rockslide toe lasted until 22 May.

The main properties of the May 2010 Girová rockslide are shown in Table 13.1, and its typical features in Figs. 13.6 and 13.7. The translational character is evidenced by terrain morphology and similar strike/dip between bedding planes outcropping in the main head scarp and gravitationally dislodged blocks. The upper part of the landslide (just below the wedge-like head scarp) experienced ca. 80 m of horizontal movement, whereas the middle section of the slope failure shifted ca. 270 m downslope. The rockslide front is a 550-m-long distal lobe partly overlying
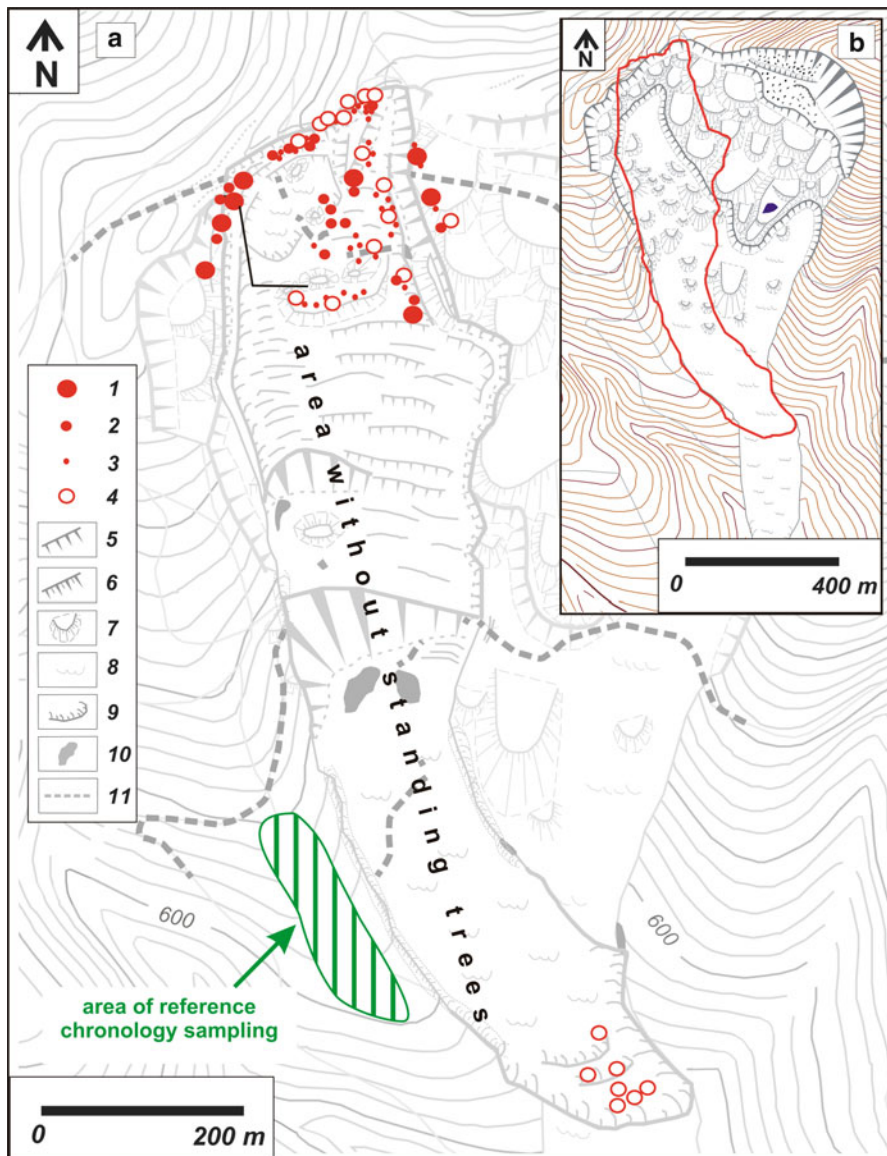
Fig. 13.6 Geomorphological map of the Girová Mountain slope deformation and localization of trees (*Picea abies*) sampled for dendrogeomorphological dating. (**a**) Reaction wood related to the May 2010 event is excluded. *1*, trees with ≥3 occurrences of reaction wood; *2*, trees with two occurrences of reaction wood; *3*, trees with one occurrence of reaction wood; *4*, trees without occurrence of reaction wood; *5*, head scarps of old landslides within DSGSD; *6*, counterslope scarps; *7*, landslide blocks; *8*, accumulation surfaces; *9*, accumulation toes; *10*, ponds within the May 2010 landslide; *11*, damaged roads. (**b**) Outline of the May 2010 failure in the context of older slope failures. (Reprinted from Geomorphology, 130/3–4, Pánek T et al., Catastrophic slope failure and its origins: Case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic), pp. 352–364, Copyright (2012), with permission from Elsevier.)

Table 13.1 Main properties of the May 2010 Girová Mountain rockslide. (Reprinted from Geomorphology, 130/3–4, Pánek T et al., Catastrophic slope failure and its origins: Case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic), pp. 352–364, Copyright (2012), with permission from Elsevier.)

Parameter	
Landslide area	20 ha
Landslide volume (approximate)	$2\text{–}3 \times 10^6 \text{ m}^3$
Landslide runout L (maximum)	1,150 m
Maximum landslide width	300 m
Elevation of head scarp	718–743 m
Elevation of terminal point	572 m
Landslide height (H)	171 m
H/L	0.15
Excess travel distance (Le)	891 m
Le/L	0.77

the older generation of long-runout landslide(s). Several ponds have survived on the surface of the distal lobe for the rest of the year 2010.

Radiocarbon dating revealed at least *three generations* of major landslides which preceded the May 2010 disastrous failure. A tree trunk incorporated in landslide accumulation underlying the recent lobe (upthrust in front of the recent failure) was dated at $7{,}420 \pm 60$ cal BP (Beta-288258) and reflects the age of the long-runout lobe (first-time landslide?) continuing ca. 500 m below the end of the May 2010 rockslide (Fig. 13.7). Another two dated samples indicate minimum ages of younger, rather short-distance movements. Dating of the basal part of the peat bog situated in the upper axis of contemporary rockslide returned the age of $1{,}540 \pm 40$ cal BP. It means that the upper part of the May 2010 rockslide has not been affected by displacements for at least the last 1,500 years. The youngest sample dated 600 ± 30 cal BP marks the onset of bog formation disturbed on the eastern margin of the catastrophic landslide in May 2010.

Dendrogeomorphological dating helped to determine the dynamics of minor, accelerated *creep*-like movements within the landslide body for 1930–2010 (Fig. 13.8). Trees in the reactivated slope section revealed 34 years with tree trunk tilting. The area of the reactivated rockslide points to an increasing frequency of years with tree tilting since the mid-1970s with the culmination in the late 1990s. Sliding/creep was triggered by an extreme hydrometeorological event in July 1997. The spatial distribution of disturbed trees is presented in Fig. 13.6. The majority of sampled trees with more than two dated disturbances indicated by reaction wood in the last 80 years are concentrated in the vicinity of the May 2010 head scarp. On the other hand, the zone of the contemporary lobe lacks any evidence of previous slope movement. The first event indicated by reaction wood in this domain comes from 2010; its origin is undoubtedly connected with the May rockslide.
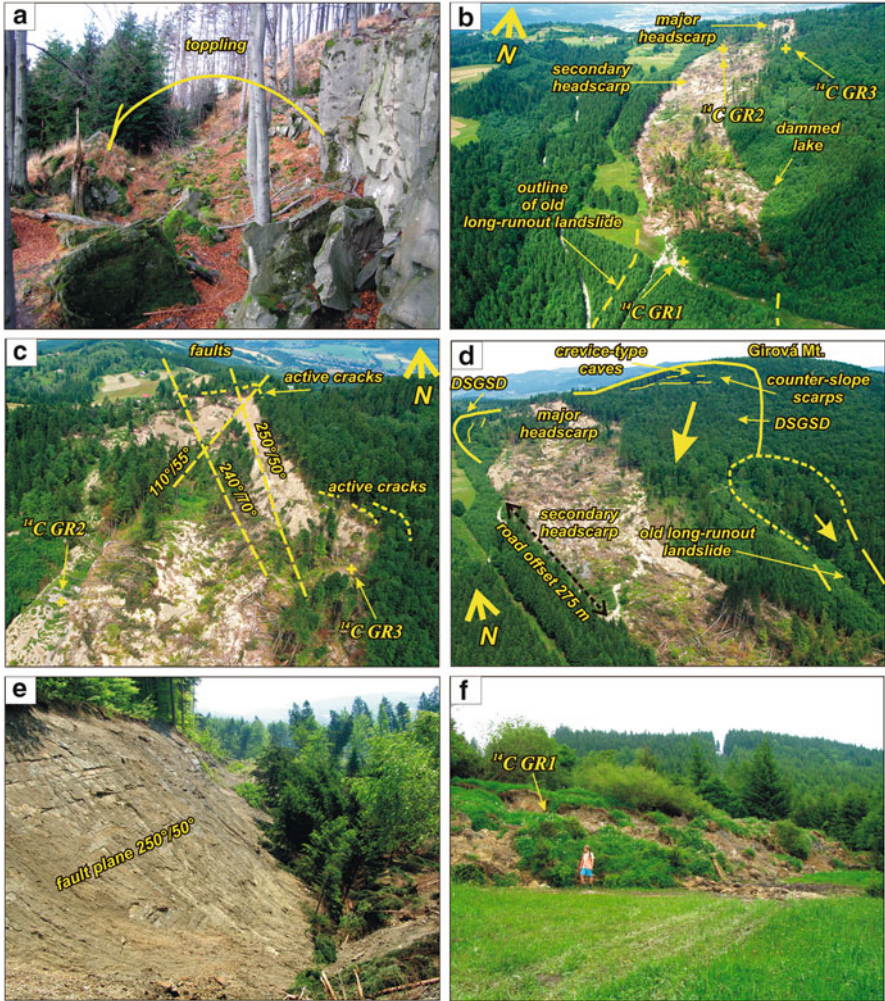
Fig. 13.7 Typical morphological features within the Girová Mountain slope deformation. (**a**) Toppling-related head scarp area of the DSGSD within sandstone-dominated flysch (Lukov Member). (**b**) Overall aerial view of the May 2010 catastrophic rockslide. (**c**) Detailed aerial view of the wedge-like depletion zone of the rockslide with marked main tectonic elements of the slope and position of dated peat bogs. (**d**) Aerial view of the upper half of the rockslide displaying relations to older slope deformations and displacement markers (destroyed road). (**e**) Main fault-predisposed head scarp of the May 2010 catastrophic rockslide. (**f**) Frontal part of the May 2010 long-runout lobe (upthrust of a precedent landslide) with a marked position of a dated buried trunk. (Reprinted from Geomorphology, 130/3–4, Pánek T et al., Catastrophic slope failure and its origins: Case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic), pp. 352–364, Copyright (2012), with permission from Elsevier.)
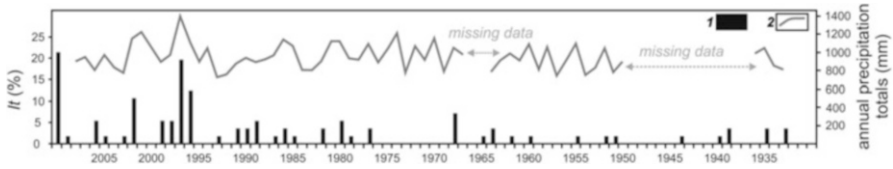
Fig. 13.8 Results of dendrogeomorphological analysis (initial occurrence of reaction wood expressed by the anomaly index). *1*, It index; *2*, annual precipitation totals. (Reprinted from Geomorphology, 130/3–4, Pánek T et al., Catastrophic slope failure and its origins: Case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic), pp. 352–364, Copyright (2012), with permission from Elsevier.)

13.6   Discussion

Along with well-saturated soil by antecedent rainfalls, extremely high precipitations (locally above 300 mm during 3 days) on 16–18 May 2010 generated more than 150 slope failures within the lithologically weak domain of the OWC and their foredeep. A strong lithological predisposition of the landslide event in May 2010 is evident from the clustering of May 2010 landslides on Quaternary deposits and/or thin-bedded flysch bedrock and the relative lack of new landslides within the highest, flysch, parts of the OWC (although heavily affected by older deep-seated landslides – see Hradecký and Pánek 2008). Apart from this, the distribution of landslides seems to be rather more closely related to that of extreme rainfalls in May 2010 and the API_{30} index than to the precipitations in 16–18 May. The majority of the landslides show characteristics of rather small reactivations of older, recurring slope instabilities. Similar situation has also been described in other flysch regions (Sabatakakis et al. 2005; Borgatti et al. 2006; Mikoš et al. 2009). The landslides typically originated on steep eroded slopes, where – besides rainfall-generated pore pressures – the role of increased shear stress due to lateral erosion of rivers at bank-full discharge was decisive (for comparison see Kim et al. 2010). The predominance of incipient failures (short-travel landslides, tension cracks) and shallow debris slides or soil slips supports the fact that the duration and intensity of the May 2010 rainfall were insufficient (except for the Girová rockslide) for the occurrence of major landslides, as compared with the situation in July 1997 (Krejčí et al. 2002). In spite of the fact that the May 2010 landslide event in the OWC was only moderately destructive, it left many initial slope failures behind with a high potential for future reactivation (for comparison, see Saba et al. 2010).

Although recently the medium-height mountains of Central Europe have only rarely been affected by such long-runout landslides (Němčok 1982; Rybář and Stemberk 2000; Migoń et al. 2002; Klimeš et al. 2009), the May 2010 Girová Mountain rockslide demonstrates that they still might evolve under specific circumstances also in settings characterized by relatively gentle hillslopes (20°) and local relief (200 m). The combination of preparatory factors within the zone of the Girová Mountain slope deformation has produced several recurrent Holocene collapses especially in its fault-preconditioned, wedge-like western margin of clay stone. At least one of these

collapses dated to the *Atlantic* chronozone (~7.4 cal ka BP) evolved into a *long-runout landslide*, whose lobe length exceeded that of the May 2010 landslide by several hundreds of meters. The age of this major failure can be correlated with numerous slope failures and flood deposits in the nearby Polish Carpathians, also dated to the very humid Atlantic chronozone (Margielewski 2006). The dating of landslide-related peat bogs within these blocks suggests that the *recurrence interval* of major slope failures within the rockslide zone is on the order of ~1 ka, presumably correlated with bedrock *relaxation time*, i.e., a period necessary for shear strength reduction as a result of weathering along wedge-like fault planes (Hartvich and Mentlík 2010).

13.7 Conclusions

Although unusual in Central Europe, merely the duration and intensity of the May 2010 rainfall event were probably insufficient for generating failures of extraordinary dimensions, such as the Girová rockslide, which remained a site-specific, isolated failure. Furthermore, even more extreme rainfall episodes of several last decades (e.g., three- to six-day precipitation amounts of 537 and 625 mm at the Šance station on 4–9 July 1997 – see Štekl et al. 2001) activated slope failures which reached at most half of the size of the May 2010 Girová Mountain rockslide (Krejčí et al. 2002). Therefore, the May 2010 rainfall event was only the final (but important) incremental change leading to the collapse of the Girová Mountain slope.

The main preconditions of slope failure were long-term, internal changes within the rock mass. As evidenced by dendrogeomorphological dating, rock strength weakening was connected to long-term (decennial-scale) creep leading to the final catastrophic movement. This creep was accelerated several times over the 1930–2010 period, mostly as a consequence of the growing rate of strain induced by hydrometeorological conditions which increased pore pressure. A similar behavior of recent disastrous deep-seated landslides was described by Petley and Allison (1997).

Dendrogeomorphological data support an assumption that the May 2010 long-runout landslide was initiated in its upper part with concentrated creeping (with some periods of accelerations) for at least 80 years before the catastrophic collapse. However, many trees from the upper part of the landslide do not reveal any year of reaction wood. It could be explained by a translational, blocklike character of movement. Some trees (e.g., standing on the boundary of sliding blocks) represent a good dendrogeomorphological signal of past failures, while trees within the internally non-deformed sliding blocks do not react to slope movements.

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