



Age and Reactivations of Catastrophic Complex Flow-Like Landslides in the Flysch Carpathians (Czech Republic/Slovakia)

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Abstract

Catastrophic complex flow-like landslides (CFLLs) are characterised by a deep-seated retrogressive landslide of structurally unfavourably oriented rocks and earthflows that occupy the lower slope positions and originate due to the liquefaction of material accumulated on the upper slopes. These landslides are locally important geomorphic agents of Late Quaternary mountain evolution in the Flysch Belt of the Outer Western Carpathians (Czech Republic/Slovakia). Most of the CFLLs dammed and steepened adjacent valleys. Radiocarbon dating suggests that a majority of them moved repeatedly throughout the Holocene, namely approx. every 1–2 ka. Dated events occurred during humid phases of the Younger Dryas/Holocene transition (11.5–9.4 cal ka BP), Atlantic chronozone (7.4–6.6 cal ka BP), the beginning of the Subboreal chronozone (ca. 4.6 cal ka BP) and, primarily, within the Subatlantic chronozone at ca. 2–0.8 cal ka BP (>50 % of all events). Our study suggests that slopes based on an unfavourable structural setting and affected by long-term deep-seated gravitational deformations may produce CFLLs, even if they are located in medium-high mountains. Although our chronological dataset is influenced by the erosion of older landforms, most of the dated reactivations correlate with regional increase in precipitation identified by previous palaeoenvironmental studies.

Keywords

Complex flow-like landslides • Radiocarbon dating • Holocene • Flysch Carpathians • Czech Republic • Slovakia

Introduction

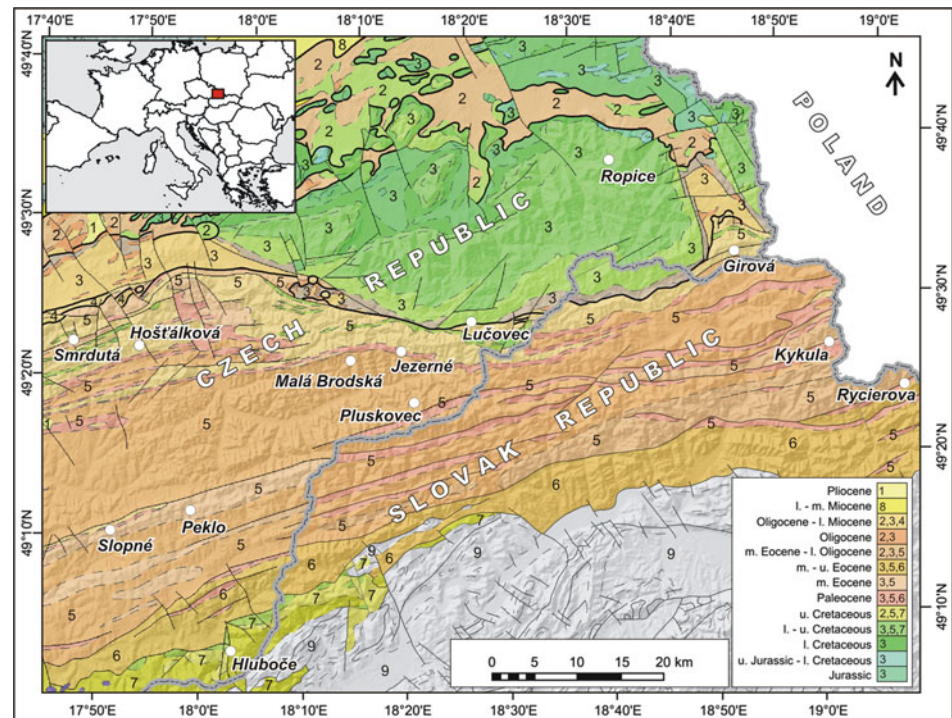
Investigation and dating of preserved deposits of ancient long-runout landslides in mountainous terrains are useful both for the elimination of landslide hazards and for the understanding of late Quaternary history. Recent field

investigations in the Flysch Belt of the Outer Western Carpathians led to the discovery of several large rotational-translational slope failures that had transformed into shallow earthflows at their frontal parts due to substrate liquefaction (Baroň et al. 2004, 2011; Pánek et al. 2013). Herein, we call such failures *complex flow-like landslides* (CFLLs) (Pánek et al. 2013). These failures correspond to complex landslides of Cruden and Varnes (1996), but using this new term we put stress on the role of flow-type behaviour during landslide emplacement. The basal sliding zone of CFLLs crops out in the upper/middle parts of deformed slopes, while in their lower positions the sliding material liquefies and evolves into earthflows. Some of these failures progressed catastrophically during heavy rainfall and snowmelt periods in 1919, 1997, 2006 and 2010 and they therefore pose a significant

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Fig. 1 Geology of the study area with locations of the studied CFLLs. Reprinted from Quaternary Research, 80, Pánek T et al., Holocene reactivations of catastrophic complex flow-like landslides in Flysch Carpathians (Czech Republic/Slovakia), p. 34, Copyright (2013), with permission from Elsevier



hazard in the study region (Baroň et al. 2004; Pánek et al. 2013).

The aims of our study are (1) to provide the evaluation of CFLLs in Flysch Carpathians together with the discussion of their imprint in geomorphic evolution of this region, (2) to determine Holocene history and recurrence of most pronounced failures and (3) to correlate the studied events with regional Holocene palaeoenvironmental and palaeoclimatological proxies. To answer such questions, a detailed study was performed of thirteen most pronounced examples of CFLLs in the study region (Fig. 1).

Regional Settings

The study area involves the western part of Flysch Carpathians situated along the border between the Czech Republic and Slovakia (Fig. 1). Flysch Carpathians comprise a fold-and-thrust belt consisting of shales, claystones and sandstones of Mesozoic and Tertiary age which were thrust onto the Northern European platform and part of its foredeep during the Palaeogene and Neogene. Anisotropic flysch strata are highly prone to landsliding, especially due to elevated pore-water pressures during extreme hydro-meteorological events such as heavy rainfall and rapid snow-melt (Margielewski 2006a). To date, more than 10,500 landslides have been documented within the region (Pánek et al. 2013).

Materials and Methods

Emphasis of this paper is on the geomorphic and chronological aspects of CFLLs with a special attention to possible recurrence. Geomorphic analyses involved the mapping of landslide deposits by means of field methods and aerial photographs. Structural conditions were evaluated in the vicinity of landslides (especially in the headscarp areas) via measurements of main discontinuity sets whose interplay with slope geometry was analyzed as well as possible kinematics of landslide movements (Margielewski 2006b).

The age of landslides was constrained by radiocarbon dating of organic material obtained either from the landslide debris (natural outcrops) or sediments connected with the evolution of landslides (i.e. deposits of dammed lakes or peat bogs on the surface of the landslides). Our strategy of landslide dating brings some uncertainties connected with both over- and underestimation of the timing of landslides. The age of organic material incorporated in landslide debris could be older than a particular landslide due to possible multiple re-deposition. Conversely, the ages of sediments trapped in dammed lakes and landslide peat bogs are younger than a particular slope failure. A total of 25 radiocarbon dates (mainly AMS) define the origin or reactivation of individual landslides (Pánek et al. 2013). Radiocarbon dates were converted into calendar ages using IntCal 09 calibration curve in OxCal v 4.1.7 software.

Results

CFLLs in the study area comprise various slope failures extending over relatively long distances (470–2,950 m) and are characterised by high mobility (10^{-1} – 10^2 m/day as stated for recent events), high volumes (0.1 – 12×10^6 m³) and significant liquefaction of displaced material in their middle to lower portions (Pánek et al. 2013). The largest group of CFLLs includes older failures (Kykula, Peklo, Slopné, Lučovec, Pluskovec) and recent catastrophic failures (January 1919 Hošťálková, July 1997 Malá Brodská, April 2006 Hluboče and May 2010 Girová landslides), which originated mainly within rock massifs containing a significant fraction of weak claystone/mudstone-dominated flysch (Fig. 2a). Failures in this group are rotational-translational or purely translational landslides combined with distal earthflows. Another group of CFLLs (Smrdutá, Ropice, Rycierova, and Jezerné) is characterised by rockslides affecting predominantly competent sandstone beds. These failures have distal, up to 1 km long tongues bearing pronounced stony accumulations with metre-scale sandstone blocks (Fig. 2b). Most of the CFLLs are spatially related to deep-seated gravitational slope deformations (DSGSDs) found along tectonic discontinuities and tectonically weakened (mainly wedge-type) zones in flysch rock masses (Pánek et al. 2013).

The ages of CFLLs in our dataset span the entire Holocene period with a strong bias towards the youngest, Subatlantic chronozone (Pánek et al. 2013). The oldest landslide (Kykula) originated in the Younger Dryas/Holocene transition (11.5–9.4 cal ka BP), while the youngest reactivation (excluding modern catastrophic failures) was identified within the Little Ice Age period (Smrdutá landslide, ca. 0.3 cal ka BP). One of the largest CFLLs (Girová landslide) originated during the extreme rainfall event of May 2010. Most of the dated landslides (75 %) have originated in the last 2,000 years, with a pronounced cluster between ca. 1.7 and 1 cal ka BP (34 % of all dated activations). Some individual events were dated to the Atlantic chronozone (7.4–6.6 cal ka BP; Girová and Peklo landslides) and the beginning of the Subboreal chronozone (ca 4.6 cal ka BP; Smrdutá and Peklo landslides) (Pánek et al. 2013).

One of the most important findings of this study is that most CFLLs are recurrent phenomena (Table 1). For instance, the Peklo landslide contains four scarps characterised by different degrees of denudation suggesting multistage evolution. This is supported by four generations of fluvio-lacustrine sediments in the adjacent dammed palaeolake dated to 7.2, 6.4, 4.5 and 0.6 cal ka BP. Generally, we can identify two chronological types of recurrences – successive major activations separated by

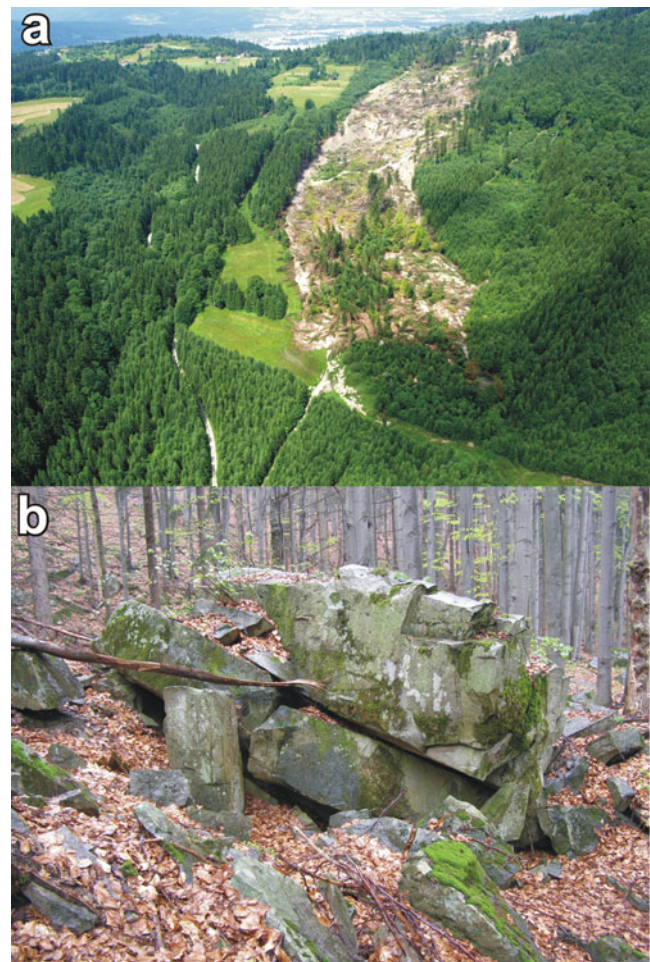


Fig. 2 Examples of CFLLs. (a) The May 2010 Girová landslide originated in the slope section with preceding landslide activity dated to 7.5, 1.5 and 0.6 cal ka BP. (b) Large sandstone blocks within the accumulation of the Rycierova rockslide (dated to ca. 1.0 cal ka BP)

short chronological intervals (up to several centuries; e.g. Kykula or Lučovec; Fig. 3), and repeated major movements after relatively long periods spanning more than one millennium (e.g. Malá Brodská landslide). Some failures from the latter group were reactivated several times throughout the Holocene (e.g. Peklo and Girová landslides). Liquefied and relatively long-runout slope failures reached valley floors and affected the geomorphic regime of mountain rivers. Except for two cases, all landslides in our dataset blocked valley floors and influenced the steepness parameters of river profiles. Sedimentological and pollen indices show that the longevity of landslide-dammed lakes before the breaching of dams spanned a variety of timescales including >2 ka for the Kykula landslide (Pánek et al. 2010), 10^2 years for the Smrdutá, Peklo and Pluskovec landslides, and 10^{-1} – 10^2 years for the Lučovec landslide (Pánek et al. 2013).

Table 1 Timing and recurrence intervals for selected CFLs [Partly reprinted from Quaternary Research, 80, Pánek T et al., Holocene reactivations of catastrophic complex flow-like landslides in Flysch Carpathians (Czech Republic/Slovakia), p. 43, Copyright (2013), with permission from Elsevier.]

Landslide	Available period (cal ka BP)	Number of dated events	Average rec. interval (ka)
Kykula	~11.5–9.4	2	2.1
Peklo	~7.2–0.6	4	2.2
Girová	~7.4–AD2010	4	2.5
Smrduť	~4.6–0.3	3	2.2
Lučovec	~1.7–0.8	3	0.4
Hošťálková	~1.4–AD1919	2	1.4
Ropice	~1.4–0.4	2	1
Hluboče	~1.3–AD2006	2	1.3
M. Brodská	~1.1–AD1997	2	1.1
Jezerné	~1.0–0.8	2	0.3

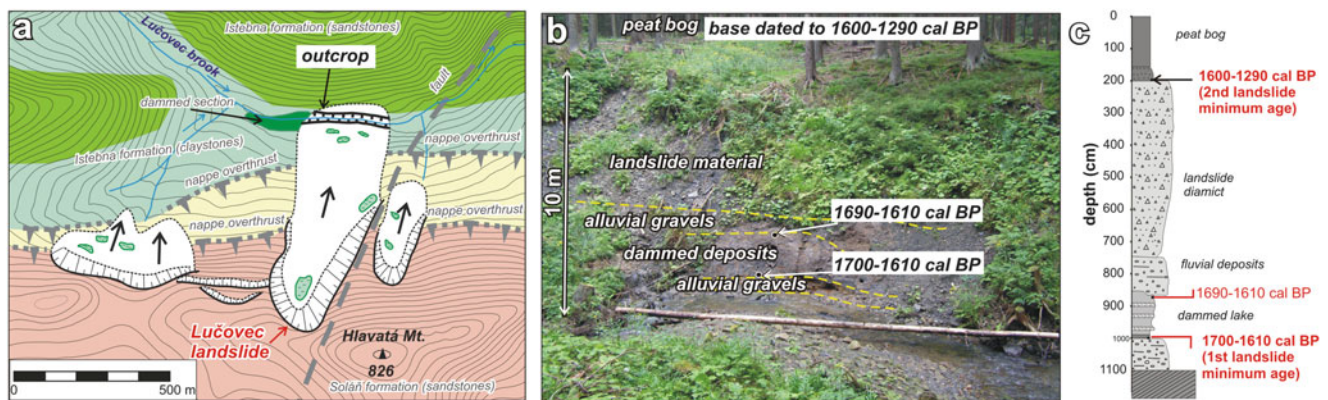


Fig. 3 A recurrent landslide in the Lučovec valley. (a) Geomorphic sketch of landslide blocking valley floor. (b) Exposure evidencing two generations of successive landslides which took place during a short

time interval between ca 1.3–1.7 cal ka BP. A possible younger retrogressive shift of headscarp took place ca 0.7 cal ka BP. (c) Interpreted stratigraphic log of the exposure

Discussion and Conclusion

A majority of CFLs in the study region fall within the Holocene period with most ages spanning to the Subatlantic chronozone (>50 % of all events) (Pánek et al. 2013). The analysis of the history of individual instabilities reveals that a majority of landslides are recurrent features with a time interval between two successive major events being in the orders of 10^1 – 10^3 years. An important issue for hazard planning is that released debris from some of recurrent catastrophic long-runout landslides has nearly reached the same position as during previous events, for example, Malá Brodská, Girová or Smrdutá landslides. As a result, some slope and valley-floor sections are particularly dangerous for human activities (Pánek et al. 2013; Fig. 2a). Factors that affect the time span between CFLs reactivations include (1) frequency of extreme hydrometeorological events (e.g. heavy rainfalls and rapid snowmelt) and (2) progressive strength degradation along major discontinuity sets

(Kemeny 2003). While hydrometeorological extremes are immediate triggers of stability changes within rock massifs, strength degradation seems to be the most important for the time span between CFLs reactivations in connection with the fact that some major failures (e.g. May 2010 Girová landslide which is one of the largest Holocene failures) originated during rather moderate hydrometeorological events (Pánek et al. 2011). The pre-failure behaviour of catastrophic landslides is often characterised by creep movements within weakened bedrock. Three major recent catastrophic events of our dataset (January 1919 Hošťálková, March 2006 Hluboče and May 2010 Girová landslides) were preceded by several years of minor instability (Pánek et al. 2013).

Our dataset (25 dated landslide events) is also limited for chronological determinations, but it shows a possible correlation with other Central European palaeoclimatological proxy records including lake-level highstands (Magny 2004), $\delta^{18}\text{O}$ speleotheme records (Niggemann et al. 2003), Alpine glacial advances (various authors in Starkel et al. 2006), palaeofloods (Starkel

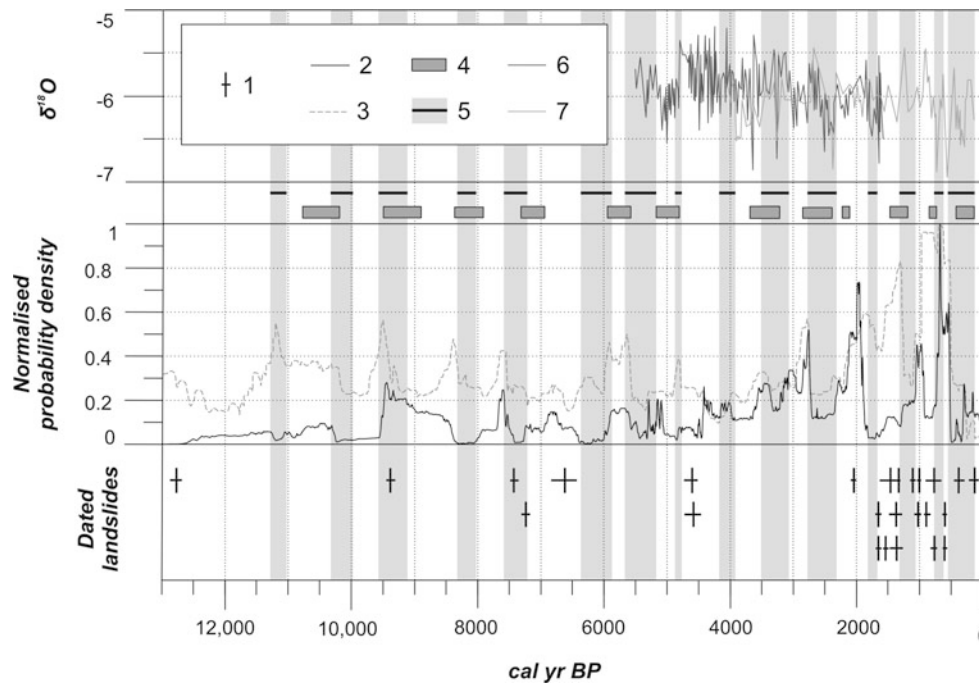


Fig. 4 Dating of individual CFFLs and their reactivations compared to the probability density curve of the Holocene dated landslide events in the Czech and Polish part of the Outer Western Carpathians and other central-European palaeoclimatological proxy records: (1) single dates of studied CFFLs (median $\pm 1\sigma$), 25 dates (Baroň 2007; Baroň et al. 2011; Pánek et al. 2009a, b, 2010, 2011, 2013); (2) normalised probability density curve of the Czech and Polish landslide events, 85 dates (Alexandrowicz 1993; Alexandrowicz and Alexandrowicz 1999; Margielewski 1997, 1998, 2001, 2003, 2006a; Margielewski and Kovalyukh 2003; Baroň 2007; Margielewski et al. 2010, 2011) and

unpublished ages of 5 landslides from the Czech part of the Outer Western Carpathians (3) normalised probability density curve of the hydrological events in Polish rivers, 331 dates (Starkel et al. 2006); (4) advances of Alpine glaciers (by various authors in Starkel et al. 2006); (5) mid-European higher lake-level phases (Magny 2004); (6) $\delta^{18}\text{O}$ record from stalagmites AH-1 and (7) B7-7 in Sauerland/Germany (Niggemann et al. 2003). Reprinted from Quaternary Research, 80, Pánek T et al., Holocene reactivations of catastrophic complex flow-like landslides in the Flysch Carpathians (Czech Republic/Slovakia), p. 44, Copyright (2013), with permission from Elsevier

et al. 2006), and timing of other landslides from the Czech and Polish Flysch Carpathians (Baroň et al. 2004; Margielewski 2006a; Margielewski et al. 2011) (Fig. 4). Highly skewed temporal distribution of CFFLs biased to the Subatlantic chronozone is most likely determined by erosion of older landslides and/or burial of ancient accumulations by debris coming from the latest stages of mass movement activity. Bias in our dataset is partly caused by types of the studied landslides, i.e. highly mobile failures with large erosive potential. In contrast to our study, a large number of predominantly short-displacement rotational bedrock landslides were dated in the Czech Carpathians by Baroň et al. (2004) and in the Polish Carpathians by Margielewski (2006a) to earlier stages of the Holocene.

To sum it up, the dating of individual CFFLs and their reactivations indicates that these mass movements originated throughout the Holocene period (Pánek et al. 2013). The largest landslides originated both at the beginning and end of the observed time period. This pattern suggests that gross conditions influencing slope stability and activation of CFFLs are relatively similar throughout

the Holocene and future sporadic large liquefied slope failures with a relatively long run-out can be expected in this region.

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