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Recent progress in landslide dating: A global overview

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Abstract

Recent progress of dating techniques has greatly improved the age determination of various types of landslides. Since the turn of the 21st century, the number of dated landslides throughout the world has increased several fold and the introduction of modern dating methods (e.g. cosmic ray exposure dating) has enabled the dating of new landslide features and elements. Based on the analysis of >950 dated landslides (of which 734 have been dated since the year 2000), it is clear that the predominant traditional strategies have continued to rely on the radiocarbon method; however, there is a remarkable trend of using cosmic ray exposure techniques for dating both the accumulation (e.g. landslide boulders) and the depletion (e.g. landslide scarps) parts of landslides. Furthermore, an increasing number of slope failures is determined by a multi-dating approach, which enables the verification of particular dating methods. Although coherent regional landslide chronologies are still relatively scarce in comparison with extensive databases of fluvial, glacial and/or eolian landforms, they offer important insights into temporal landslide distribution, long-term landslide behavior and their relationships with paleoenvironmental changes. The most extensive data sets exist for the mountain areas of North America (Pacific Coast Ranges), South America (Andes), Europe (Alps, Scottish Highlands, Norway, Carpathians and Apennines), the Himalaya-Tibet orogeny and the Southern Alps of New Zealand. Dated landslides in the plate interiors are lacking, especially in South America, Africa and Australia. Despite the fact that some dating results are well correlated with major regional and continental-scale changes in the seismic activity, moisture abundance, glacier regimes and vegetation patterns, some of these results contradict previously established straightforward hypotheses. This indicates the rather complex chronological behavior of landslides, reflecting both intrinsic (e.g. gradual stress relaxation within a rock mass) and external factors, including high-magnitude earthquakes or heavy rainfalls.

Keywords
dating, landslides, paleoenvironmental proxies, Quaternary, regional landslide chronologies

I Introduction

The determination of age represents an important step towards understanding the causes, frequency and hazards connected with landslides (Corominas and Moya, 2008; Lang et al., 1999). Dated landslides might serve as significant paleoclimatic (e.g. Bookhagen et al., 2005) and/or paleosesmic (e.g. Aylsworth et al., 2000) proxies, and they are often the basis for paleoenvironmental landscape reconstructions (Borgatti et al., 2007), estimations of catchment-scale erosion rates (Antinao and Gosse, 2009) and regional

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geomorphic interpretations (Hewitt et al., 2011). Knowledge about the temporal occurrence of landslides in a given area may also help to decipher the recent and future responses of slope instabilities to climate change (Borgatti and Soldati, 2010; Huggel et al., 2011; Stoffel and Huggel, 2012).

Since the turn of the 21st century, there has been marked progress in the precision, accuracy and availability of geochronological techniques (Walker, 2005). As many new geochronological methods (e.g. AMS radiocarbon and cosmogenic exposure age dating) have become routine during the last decade, there has been a substantial increase in the number of dated landslides throughout the world. However, extensive regional landslide chronologies are still extremely scarce and are limited to only a few regions in contrast to the widespread regional or continental-scale databases of dated fluvial, glacial and/or eolian sediments and landforms (e.g. Halfen and Johnson, 2013; Hughes et al., 2013; Macklin et al., 2012). This fact is partly related to difficulties in landslide dating (e.g. a chronic lack of datable elements, frequent small-scale reactivations masking the main formative landslide events) and to the general lesser attractiveness of landslides for study by Quaternary scientists. Landslides are not as robust paleoclimate proxies as fluvial, glacial and/or eolian sediments which reflect regional-scale changes in moisture and temperature regimes. Indeed, the origin of slope failures is often connected with site-specific intrinsic factors (e.g. gradual rock strength degradation; Kemeny, 2003) without a link to any obvious regionally relevant climatic or seismic triggers (e.g. Hancox et al., 1999).

Based on a review of >950 dated landslides throughout the world, this paper aims to outline advances in landslide dating since the beginning of the new millennium, i.e. since the book of Matthews et al. (1997) and the paper of Lang et al. (1999), which provided systematic introduction to the dating of mass movements. During this period, the vast majority of landslide dating has been performed. Therefore, for the first time we can reliably evaluate the long-term behavior of various types of mass movements and can give them an absolute chronological framework. The main concern of this review is to evaluate the dating of terrestrial landslides on timescales of $\geq 10^2$ years, i.e. with a particular focus on prehistoric mass movements datable mostly by radiometric techniques. Therefore, this paper only marginally discusses methods that are based on the analysis of historical sources, lichenometric and dendrogeomorphic techniques, i.e. classic dating methods with a timespan that is limited to the last few centuries (Lang et al., 1999). The technical background of specific dating techniques (e.g. Optical Stimulated Luminescence, Cosmic Ray Exposure Dating) has been the recent focus of numerous comprehensive studies (e.g. Fuchs and Lang, 2009; Gosse and Phillips, 2001; Stokes, 1999); therefore, this paper does not provide further insight into the geochronological methods themselves. The principal aims are as follows: (1) to describe the recent trends in using various landslide dating techniques and strategies; (2) to provide a regional overview of dated landslides throughout the world; and (3) to outline the main implications of new chronological findings for understanding the spatiotemporal behavior of slope failures.

II Landslide dating: classic approaches and recent trends

1 Summary of landslide dating methods

The basic characteristics and categorization of landslide dating methods have been presented in several previous studies (e.g. Corominas and Moya, 2008; Jibson, 1996, 2009; Lang et al., 1999) (Figure 1). Therefore, we provide only a brief description of the most important techniques and include only the most representative references. When distinguishing between absolute and relative dating, the traditional view

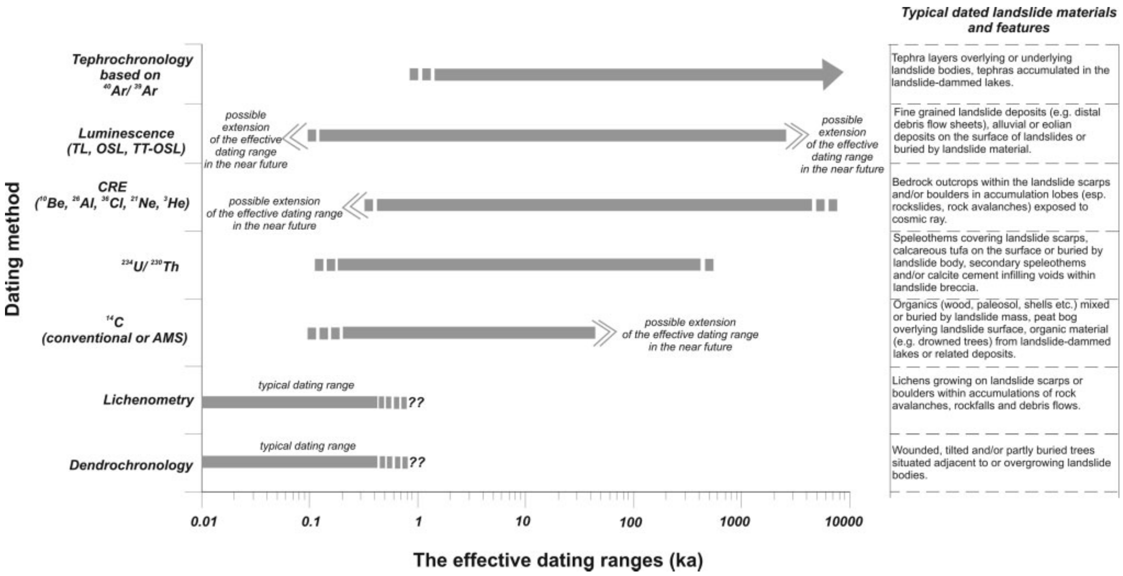

Figure 1. Major dating methods used for landslide age determinations. Some potential improvements in the effective dating ranges are outlined.

implies that absolute dating produces computed numerical ages, whereas relative dating implies only the order of events (Walker, 2005).

The most frequent absolute dating methods comprise radiometric techniques involving radiocarbon (^{14}C), Cosmic Ray Exposure (CRE), Optically Stimulated Luminescence (OSL), Thermoluminescence (TL) and Uranium-series ($^{234}U/^{230}Th$) dating (Figure 1). For timescales comprising the last few centuries, dendrochronologic (tree ring-based) techniques are also used. Radiocarbon dating has the longest tradition in the field of absolute landslide dating (since the work of Stout, 1969) and allowed performing of most extensive regional landslide chronologies (e.g. Borgatti and Soldati, 2010). CRE dating is emerging, particularly in the last decade, and enables the determination of landslide by dating both of the accumulation parts of landslides (Ballantyne et al., 2014a) and head scarps with bedrock exposures (Le Roux et al., 2009). The applications of OSL, TL and Uranium-series techniques have far more limitations in the process of landslide dating (Li et al., 2008; Prager et al., 2008; Thomas and Murray, 2001). Theoretically, all of these methods may be used to determine the minimum, maximum or the event ages (sensu Lang et al., 1999, and Corominas and Moya, 2008) depending on whether a datable landslide element is located on (e.g. Uranium-series dating of speleothems covering a landslide scarp; Pánek et al., 2009), below (e.g. OSL dating of fine-grained alluvia buried by a landslide lobe; Sewell and Campbell, 2005) or is mixed with the landslide body (e.g. ^{14}C dating of tree stems entrained in landslide material; Friele and Clague, 2004). Dendrochronologic techniques and their role in mass movement dating (mainly rockfalls, debris flows and earthflows) have been recently highlighted by numerous reviews (Stoffel, 2010; Stoffel and Bollschweiler, 2008; Stoffel et al., 2013; Trappmann and Stoffel, 2013). In some cases, tree rings allow for the determination of landslide reactivations with subannual precision (Lopez Saez et al., 2012), making this approach the most accurate and precise in the field of absolute dating methods of mass movements. The specific category of techniques that provide the numerical ages of landslide events are those that rely on historical sources, such as press archives, old maps or aerial photographs (Domínguez Cuesta et al., 1999; Raška et al., 2014).

Most of the approaches for relative dating are based on rock weathering (e.g. weathering rinds, Schmidt Hammer rebound values or rock varnish microlaminations (Clark and Wilson, 2004; Douglass et al., 2005; Mills, 2005; Orwin, 1998; Whitehouse, 1983), soil-development indices (Migoń et al., 2014; Mills, 2005; Terhorst et al., 2009) and lichenometry (Bajgier-Kowalska, 2008; Bull, 2003; Bull et al., 1994). All of these methods are related to datable elements that are located on the landslide surface and, therefore, express the minimum age of the slope failure (Lang et al., 1999). Some studies have focused on the calibration of relative dating results against certain absolute ages making them semi-quantitative methods (Aa et al., 2007; Bajgier-Kowalska, 2008; Bull, 2003; Whitehouse, 1983). However, such data are usually spatially limited and, even in such circumstances, their relevance is often subject to doubt (Smith et al., 2012). Among the techniques standing between absolute and relative dating methods is tephrochronology, which provides the minimum or maximum age constraints for a given landslide, depending on the particular tephra layer (determined, for example, by ^{40}Ar/^{39}Ar dating or fission-track dating of glass within tephra), which overlies or underlies the landslide body (Hermanns and Schellenberger, 2008; Hermanns et al., 2000; Mercier et al., 2013; Moreiras, 2006). The specific category represents palynological, carpological and paleontological methods, but they are rarely used without the support of radiometric data (Dowell and Hutchinson, 2010).

2 How do we actually determine landslide age?

As mentioned above, there are numerous possible absolute and relative dating methods that are theoretically applicable to mass movements (Corominas and Moya, 2008; Lang et al., 1999), but only a few of them have been applied to the determination of landslide age in practice (Figure 2). Some promising techniques (e.g. the Alpha Recoil Track technique) proposed by Lang et al. (1999) have probably never been used in the context of landslide dating. However, even some well-established techniques (e.g. OSL, TL or lichenometry) seem to be applicable only in very specific circumstances.

Figure 2A shows the proportion of particular methods used for dating 734 landslides and their reactivations, which were published between the years 2000 and 2013. For comparison, we also separately display the landslides (178 cases), which were dated before this period. In spite of the fact that ^{14}C dating (characterized by increasing importance of the AMS technique) still dominates (~75% of the dated landslides), there is a clear tendency indicating the increasing popularity of the CRE method, with ~18% of the dated landslides published between the years 2000 and 2013. The use of other dating techniques, from which only the OSL, ^{234}U/^{230}Th and tephrochronology are notable, reaches merely ~7% in the whole data set of dated landslides (Figure 2A). Before 2000, only a negligible fraction of landslides (~0.01%) was dated using CRE and other methods (Figure 2A).

Another important implication is related to the statistics of the most frequently used datable landslide materials and features (Figure 2B). Taking into account the whole history, most dating concerned landslide material itself, predominantly admixtured organics (40%), followed by elements located on the landslide surface (16%), CRE dating of landslide debris (13%), sediments of landslide-dammed lakes (10%), materials located below the landslide body (10%) and landslide-related turbidites and minerogenic deposits within adjacent reservoirs (7%). The CRE dating of landslide scarps represents a rather negligible fraction (3%) of the

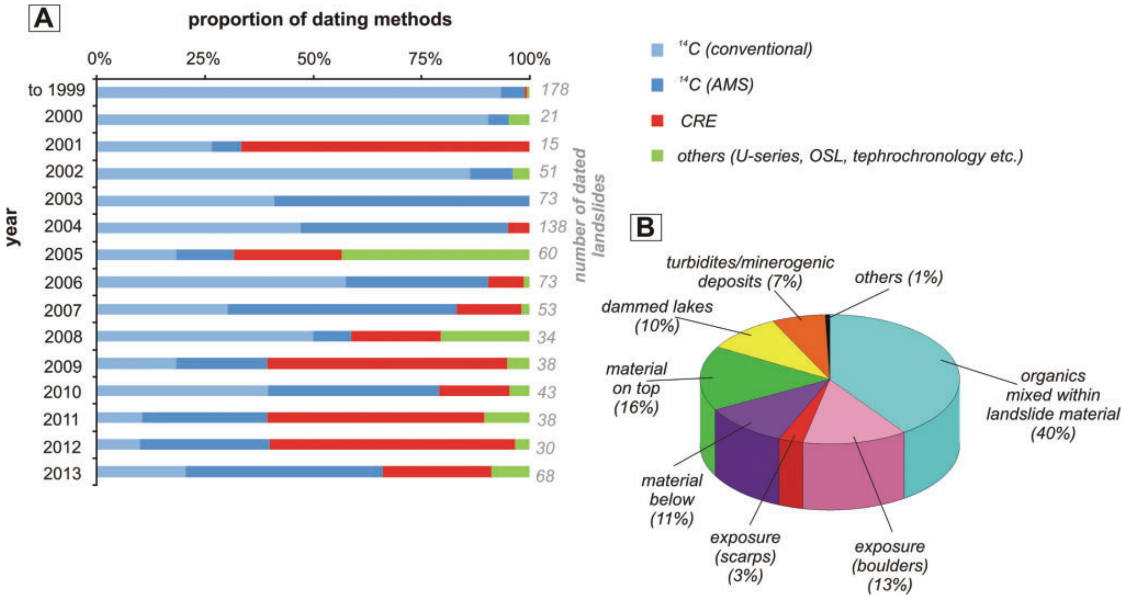

Figure 2. Using individual dating methods and landslide elements for timing landslides. (A) The proportion of individual methods used for landslide dating in studies before and after the year 2000. (B) The landslide elements and associated features and materials used for landslide age determination across the history of mass movement dating. Note that the statistics do not include relative dating methods and dendrogeomorphology.

dated landslide elements, but this strategy seems to be very promising for the age determination of rock slope failures, and its percentage will certainly rise in the near future.

3 New techniques – new challenges

Emergence of new dating techniques combined with improved precision and the effective dating ranges of certain frequently used radiometric methods have fostered substantial challenges for the determination of landslide ages. Some examples of these trends are summarized in Table 1.

Due to the introduction of new techniques, especially CRE, and to the fact that their use has become routine over the last decade, the number of datable elements within landslide bodies has substantially increased. This trend has generated new challenges; now it is possible to provide reliable time constraints for the types of mass movements, for which absolute age determination was previously impossible or very difficult. The classic examples include sackung-type slope failures, which are represented by short-travelled, mountain-scale deformations that usually enable only limited possibilities for traditional ^{14}C dating. If this method is used, these sites (e.g. organic-infilled depressions behind anti-slope scarps) can only be sampled by trenching (Agliardi et al., 2009; McCalpin and Irvine, 1995; McCalpin et al., 2011), which is extremely difficult, if not unrealistic, in remote mountain terrains. The application of CRE dating in such circumstances is logistically much simpler and only requires the presence of relatively unweathered bedrock-exposing scarps. Furthermore, the CRE dating of sackung scarps not only provides information about exposure ages (Hippolyte et al., 2006; Lebourg et al., 2014; Sanchez et al., 2010), but the dating of multiple samples along vertical profiles on

Table 1. Examples of recent trends influencing the progress of landslide dating.

Improvement/ progress	Examples	Implications for landslide dating	Main references
Availability of new radiometric methods	Mainly in-situ exposure dating by cosmogenic radionuclides ^{10}Be, ^{26}Al, ^{36}Cl, ^{21}Ne and ^{3}He	Age determination of a wider spectrum of mass movements (e.g. rock slope failures, deep-seated slope failures), reconstruction of slip-rates on landslide scarps and sackung faults, extension of regional databases of dated landslides	Hermanns et al. (2001); Hewitt et al. (2011); Hippolyte et al. (2009, 2012); Le Roux et al. (2009); McIntosh and Barrows (2011); Penna et al. (2011); Zerathe et al. (2014)
Dating method precision	Improvements in the CRE and OSL techniques, increased availability of local production rates of cosmogenic radionuclides, wider use of AMS ^{14}C dating, wiggle matching for ^{14}C dating	Inferring landslide chronologies with a higher resolution, possibility of dating of still younger ($\leq 10^2$ yrs) mass movement events	Akçar et al. (2012); Ballantyne et al. (2014a); Brooks (2013); Geertsema and Clague (2006); Merchel et al. (2014)
Effective radiometric method dating range	Introduction of thermally transferred OSL (TT-OSL)	Age determination of very old ($\geq 10^5$–10^6yrs) slope failures, incorporation of slope failures into long-term geomorphic reconstructions	Ryb et al. (2013)
New dating strategies	^{234}U/^{230}Th (and ^{14}C) dating of secondary calcareous cement and speleothems within both landslide accumulations and depletion zones, ^{14}C and thermoluminescence dating of material within shear surfaces; a multi-dating approach	Age determination of a wider spectrum of mass movements (e.g. rock slope failures affecting carbonate rocks), dating the pre-failure stages of rockslides and rock avalanches (e.g. dating of speleothems within crevice-type caves or calcite veins infilling landslide cracks)	Baroň et al. (2013); Dong et al. (2014); Ostermann and Sanders (2009); Pánek et al. (2009); Prager et al. (2009); Urban et al. (2013); Zhang et al. (2011)
Implementation of paleoseismic techniques to mass movement research	Trenching within depletion zones (e.g. anti-slope scarps of sackung-type slope deformations) and accumulation parts of landslides and the application of particular radiometric methods (mainly ^{14}C AMS and OSL)	Age determination of a wider spectrum of mass movements (esp. sackung-type slope deformations) and the reconstruction of their deformation phases and slip rates	Agliardi et al. (2009); Carbonel et al. (2013); Demoulin et al. (2003); Gutiérrez et al. (2008, 2010, 2012a, 2012b); Gutiérrez-Santolalla et al. (2005); Lee et al. (2009); McCalpin and Hart (2003); McCalpin et al. 2011); Pánek et al. (2011b)

scarps might also reveal the slip rates of individual sackung faults (Hippolyte et al., 2009, 2012). For the Séchilienne landslide (French Alps), such an approach was even extended to constrain the continuous evolution of ~30 m high head scarp (Le Roux et al., 2009). The application of three vertical profiles containing 22 ^{10}Be-dated samples on a subvertical scarp revealed a complex evolution of slope failure, involving both the continuous displacement of a major landslide body since ~6.4 ka BP and a secondary rockfall from the rock face (Le Roux et al., 2009).

One of the most indisputable improvements in the application of the CRE technique is the timing of large ($>10^6$ m^3) catastrophic rockslides and rock avalanches, especially those that are situated in arid mountain ranges with limited applicability for traditional ^{14}C dating. There have been many discussions about the potential ages of such failures, but most of these features have remained undated up to the turn of the new millennium (Hewitt, 1999). Presently, there is an available increased data set of dated rock avalanches from the Andes (Antinao and Gosse, 2009; Fauqué et al., 2009; Hermanns et al., 2001, 2004; Penna et al., 2011), Himalayas (Dortch et al., 2009; Hewitt et al., 2011; Mitchell et al., 2007), Pamir (Yuan et al., 2013) and Tien Shan (Sanhueza-Pino et al., 2011) mountain ranges.

Although not used as CRE dating, other methods are also increasingly available and/or have recently exhibited improved technical progress in the timing of landslides. The introduction of thermally transferred OSL (TT-OSL) dating might significantly extend the chronological range of classical OSL technique to $\geq 10^6$ years, as was illustrated by Ryb et al. (2013) in an example of landslides from Israel. The boom of AMS ^{14}C dating is partly responsible for the contemporary widespread application of trenching for unravelling the displacement history of sackungen and deep-seated landslides (e.g. Carbonel et al., 2013; Gori et al., 2014; Gutiérrez et al., 2008, 2010, 2012a, 2012b; Gutiérrez-Santolalla et al., 2005; McCalpin et al., 2011). This is because typically only small charcoals that are only datable with the AMS method are available in sedimentary sequences behind rotated blocks and sackung-related anti-slope scarps. Other promising dating methods involve ^{234}U/^{230}Th, which can be applied to several landslide materials and features (e.g. speleothems covering head scarps or calcite cements in rockslide deposits (Pánek et al., 2009; Prager et al., 2009; Sanders et al., 2010). As was suggested by Pánek et al. (2009), ^{234}U/^{230}Th-dated speleothems covering the walls of head scarps and gravitational trenches might provide reliable time constraints for the evolution of rock slope failures in karst areas. However, more utilization of U/Th-series dating is expected for carbonate-lithic mass movement deposits (Ostermann and Sanders, 2009; Sanders et al., 2010). An example of a Fernpass rockslide (Northern Calcareous Alps, Austria) indicated that the age of ^{234}U/^{230}Th-dated calcareous cement (4.15 ± 0.1 ka) from rockslide debris was well correlated with the in-situ ^{36}Cl exposure age of a rockslide scarp (4.1 ± 1.3 ka) and with AMS radiocarbon dated backwater deposits that were sampled behind a rockslide barrier (3.38–3.08 ka) (Prager et al., 2009). This has a major implication for dating other carbonate rock slope failures that are lacking datable organic remains.

4 Some limitations and problematic issues of dating approaches

The extensive data set of landslide-related radiometric ages that have been published in the last decades enables the evaluation of the reliability of particular dating techniques and the importance of various datable landslide elements needed for establishing the timing of landslides. The primary problems with particular dating methods were previously stated by Lang et al. (1999), but an analysis of the expanded contemporary database of dated landslides could pinpoint these issues more specifically.

A discussion is required about the interpretation of radiocarbon dating of organics that are mixed within the slide mass, which represents the most common strategy, by far, of landslide dating. Some authors argue that the dating of such organic remnants provides direct evidence, i.e. the event age of the mass movements (Corominas and Moya, 2008; Lang et al., 1999; Prager et al., 2008). However, the majority of studies presenting the dates of multiple organic remnants (e.g. several tree stumps) within a single generation of landslides reveal that the ages are seldom statistically confident and, therefore, that they reflect the entrainment of older organic remnants during the transport of landslide debris over various substrates (Brooks, 2013; Jerz and Poschinger, 1995; Orwin et al., 2004; Pánek et al., 2013b; Poschinger and Haas, 1997). Dufresne et al. (2010) noted that dated organic remnants could differ by even several thousand years within a single landslide diamicton, especially when the landslide enters a wetland area containing peat bog sequences with fossil organics. In such circumstances, and with the exception of a few specific situations (e.g. in-situ tree stumps buried by landslide material; Van Dissen et al., 2006), the age of organic material embedded within a landslide matrix should always be considered (similarly to elements overlaid by landslides) as a proxy for the maximum age of landslide events.

Similar implications are also shown in the CRE ages of landslide debris, which could reveal both overestimated ages for individual boulders (in the case of nuclide inheritance from older rock surfaces) and underestimated ages (in the case of post-depositional toppling, erosion or exhumation of boulders). Despite the fact that most published studies present coherent populations of ages for individual landslide accumulations, where single outliers can be eliminated by simple statistical treatment (Ballantyne et al., 2014a; Dortch et al., 2009; Hewitt et al., 2011; Ivy-Ochs et al., 2009; Mitchell et al., 2007; Yuan et al., 2013), some cases indicate that the exposure age variations of boulders within particular landslide accumulations might exceed 10^4–10^5 years (Antinao and Gosse, 2009; Sanhueza-Pino et al., 2011; Sewell et al., 2006). Therefore, special care should be applied to determine whether variations of ages within the dated population of boulders reveal successive generations of slope failures or rather erroneously selected sampling sites. Obvious problems also remain concerning the exposure dating of landslide scarps because these are the subject of very dynamic post-emplacement processes (e.g. rockfalls, topples). In such cases, distinguishing between the main formative events and the secondary collapses requires the statistical evaluation of large populations of dated samples (Martin et al., 2014; Recorbet et al., 2010).

5 Multi-dating approach

As mentioned above, uncertainties in the timing of landslide events could be solved using a multi-dating approach, i.e. combining several independent methods and/or datable landslide elements to determine the timing of a particular slope failure as reliably as possible (e.g. Dong et al., 2014; Friele and Clague, 2004; Prager et al., 2009; Sanhueza-Pino et al., 2011; Sewell and Campbell, 2005). Despite being still relatively rare, such studies are of a high methodical value because they provide the most reliable time constraints of individual landslides and represent an important verification of particular dating strategies (Table 2). In this respect, we particularly need to discuss approaches that focus on elements inferring the minimum age of landslides – especially peat bogs on top of landslide bodies and lakes behind landslide barriers (e.g. Geertsema and Schwab, 1997;

Table 2. Selection of landslides dated using several independent techniques and a comparison of their age results.

Landslide/region	Latitude	Longitude	Landslide characteristics	Methods used	Results of dating (cal ka BP)[a]	References
Pylon Peak-older/Coastal Range (Canada)	50.5618°	–123.478°	Volcanic debris flow/rock avalanche	^{14}C dating of organics within landslide material	9.94–8.5	Friele and Clague (2004)
				^{36}Cl exposure dating of landslide deposits	7.5–6.0	
Flims/Alps (Switzerland)	46.861°	9.257°	Rock avalanche	^{14}C dating of organics within landslide material	10.16–8.21	Deplazes et al. (2007); Poschinger and Haas (1997); Schneider et al. (2004)
				^{14}C dating of lake deposits overlying landslide	9.05–8.4	Deplazes et al. (2007)
				^{36}Cl exposure dating of landslide scarps and deposits	9.52–8.2	Ivy-Ochs et al. (2009)
Fernpass/Alps (Austria)	47.359°	10.832°	Rockslide/rock avalanche	^{14}C dating of dammed lake deposits	3.38–3.08	Prager et al. (2009)
				^{234}U/^{230}Th dating of calcareous cement within landslide deposit	4.43–4.12	
				^{36}Cl exposure dating of landslide scarps	4.8–3.4	
Tschirgant/Alps (Austria)[b]	47.237°	10.824°	Rockslide/rock avalanche	^{14}C dating of organics within landslide material	3.89–2.74	Patzelt and Poscher (1993) and Patzelt (2004) in Prager et al. (2008)
				^{234}U/^{230}Th dating of soda-straw stalactites within landslide deposits	3.65–2.8	Ostermann and Sanders (2009)
Chironico/Alps (Switzerland)	46.417°	8.852°	Rockslide	^{14}C dating of dammed lake deposits	13.73–13.05	Antognini and Volpers (2002)
				^{10}Be exposure dating of landslide deposits	14.66–12.77	Claude et al. (2011)
Alamyedin/Tien Shan (Kyrgyzstan)	42.609°	74.665°	Rockslide	^{14}C dating of gastropod shells in loess incorporated within landslide deposit	15.28–10.28	Sanhueza-Pino et al. (2011)
				^{10}Be exposure dating of landslide deposits	13.6–11.7	

[a] Age ranges are based mostly on multiple samples; outliers are not presented.

[b] Probably two generations of mass movements.

Margielewski, 2006; Mercier et al., 2013; Pánek et al., 2013b). Both often represent the only possibility for dating of internally non-fragmented rotational and translational slides (Lang et al., 1999). When results are compared from combinations of dating overlying peat bogs and/or dammed lakes with other independent approaches, we see that the majority of results are (if not statistically indistinguishable) similar on decennial to centennial timescales (Table 2). Good results particularly show radiocarbon dated basal sequences of landslide-dammed lakes, which excellently fit other independently dated landslide materials and features, e.g. organics embedded within mass movement deposits (Geertsema and Clague, 2006; Goto et al., 2010) or landslide boulders or scarps that were dated by in-situ cosmogenic ^{10}Be or ^{36}Cl nuclides (Claude et al., 2011; Prager et al., 2009). This finding is of major importance for the landslide dating practice because 10% of realized landslide dating relies on the ages of impounded deposits behind landslide dams. Therefore, despite being generally categorized as a relative dating approach (Lang et al., 1999), more than a decade of experience shows that the basal sequences of landslide dammed lakes provides one of the most reliable and accurate approximations of landslide ages (e.g. Antognini and Volpers, 2002; Borgatti et al., 2007; Dong et al., 2014; Geertsema and Clague, 2006; Pánek et al., 2013b). Moreover, despite the fact that peat bogs and dammed lakes need time to evolve after a landslide event (Lang et al., 1999), such a delay is typically within the errors of absolute dating techniques; i.e. 10^1–10^3 years. This implies that in most cases, and with the typical precision of contemporary dating techniques, carefully provided 'minimum' dating will return ages that are not significantly different from dated landslide elements that are traditionally considered to approximate 'event ages' (Corominas and Moya, 2008).

In some extreme cases, using two or more independent radiometric techniques for the same material could reveal major implications for a particular geochronological technique, as was demonstrated by Zerathe et al. (2013) who dated two rockslides in the Maritime Alps in France with in-situ produced ^{10}Be and ^{36}Cl on exposed chert (diagenetic silica) concretions. A major discrepancy was exhibited between the exposure ages generated by both of the radionuclides and represents the limits of ^{10}Be cosmogenic exposure dating for this type of rock material.

III Global overview of dated landslides

A worldwide summary of the most important studies about the absolute timing of landslides is provided in Table 3. One important piece of evidence indicates that the distribution of dated landslides is highly spatially asymmetric (Figure 3). It is clear that certain relevant studies (e.g. those published as research reports or papers in local journals) might be omitted in this review and a percentage of landslide dating (e.g. in the USA and Canada) has been performed by consultants in private studies that are not publicly available (J. McCalpin, personal communication, 2014).

Extensive data sets are becoming available, especially for mountain regions throughout the world such as the high mountains of North and South America, the European Alps, the Scottish Highlands, Norway, the Carpathians, the Apennines, the Himalaya-Tibet orogeny and the Southern Alps of New Zealand (Table 3). However, there are virtually no data for regions outside the major mountain belts, like the tablelands in the plate interiors, valleys of major rivers incising platform areas or for coastal areas. In fact, some of these regions are crucial for understanding the geomorphic response from climate change. For instance, it would be of major paleoenvironmental significance to infer the age of pronounced clusters of giant landslides that are situated in contemporary arid regions like the central Sahara (Busche, 2001) or the Caspian Lowlands (Pánek et al., 2013a).

Table 3. Regions with well-established landslide chronologies.

Continent	Region	Number of dated landslides[1]	Predominant type of dated landslides/comment	Dating methods used	Main references[2]
North America	Pacific Coast Ranges (Canada/USA)	>53	Debris flows and landslides in sensitive clays. Few rock avalanches and sackung-type slope deformations.	^{14}C (96%), ^{10}Be, ^{36}Cl	Clague et al. (2003); Friele and Clague (2004); Friele et al. (2008); Geertsema and Schwab (1997); Jacoby et al. (1992); McCalpin and Hart (2003); Orwin et al. (2004); Schuster et al. (1992); Simpson et al. (2006)
	Rocky Mountain System and Intermontane Plateaus (USA/ Canada)	>14	Rotational landslides, rock avalanches and sensitive clay flowslides. Few sackung-type slope deformations.	^{14}C (76%), ^{3}He, ^{10}Be	Hylland and Lowe (1998); McCalpin and Irvine (1995); Marchetti et al. (2007); Nichols et al. (2006); Reneau and Dethier (1996)
	Great Plains/Alberta Plateau (Canada)	>18	Landslides and earthflows in clayey sediments	^{14}C	Geertsema and Clague (2006); Geertsema and Foord (2014)
	Quebec and Ontario (Canada)	>28	Landslides in sensitive clays	^{14}C	Aylsworth et al. (2000); Brooks (2013)
	Appalachian Mountains (USA)	>11	Debris flows	^{14}C	Eaton et al. (2003)
South America	Andes (Argentina, Chile and Peru)	>66	Rock avalanches and rockslides, few debris flows	^{36}Cl (32%), ^{14}C (26%), ^{21}Ne (13%), ^{10}Be (11%), ^{3}He+^{21}Ne (6%), tephrochronology (6%)	Antinao and Gosse (2009); Costa and Gonzáles Díaz (2007); Fauqué et al. (2009); Hermanns and Longva (2012); Hermanns et al. (2001, 2004); Keefer et al. (2003); Penna et al. (2011); Trauth and Strecker (1999); Welkner et al. (2010)
Europe	British Islands (UK and Ireland)	>48	Rock avalanches, rockslides and rockfalls, few rotational and translational landslides	^{10}Be (60%), ^{14}C (35%), ^{36}Cl	Ballantyne and Stone (2013); Ballantyne et al. (2013, 2014a, 2014b); Dowell and Hutchinson (2010)
	Scandinavian Mountains (Norway)	>74	Rockslides, rock avalanches and debris flows. Few dated landslides in sensitive clays.	^{14}C (97%), ^{10}Be	Aa et al. (2007); Blikra et al. (2006); Bøe et al. (2003, 2004); Fenton et al. (2011); Matthews et al. (2009); Solberg et al. (2008)

(continued)

Table 3. (continued)

Continent	Region	Number of dated landslides[1]	Predominant type of dated landslides/comment	Dating methods used	Main references[2]
	Alps (Austria, Italy, Switzerland, France, Germany, Slovenia)	>215	Diverse variety of landslides. Rock avalanches/rockslides, earth flows and debris flows dominate. Few dated sackung-type slope deformations.	^{14}C (86%), ^{10}Be (8%), ^{36}Cl (6%), OSL	Bigot-Cormier et al. (2005); Borgatti and Soldati (2010); Cossart et al. (2008); Dapples et al. (2002); Delunel et al. (2010); Hippolyte et al. (2009, 2012); Ivy-Ochs et al. (2009); Le Roux et al. (2009); Merchel et al. (2014); Mignon (1971); Patzelt (1987); Pellegrini et al. (2004); Prager et al. (2008, 2009); Sanchez et al. (2012); Soldati et al. (2004); Unkel et al. (2013); Zerathe et al. (2014)
	Northern Iberia/ Pyrenees (Spain and France)	>41	Earthflows and sackung-type slope deformations	^{14}C (93%), OSL, ^{10}Be	García-Ruiz et al. (2003); González-Díez et al. (1999); Gutiérrez et al. (2008, 2010, 2012a, 2012b); Gutiérrez-Santolalla et al. (2005); Lebourg et al. (2014); Moya et al. (1997)
	Apennines (Italy)	>53	Earthflows, few dated rock avalanches and sackung-type slope deformations	^{14}C (98%), ^{234}U/^{230}Th	Bertolini (2007); Bertolini et al. (2004); Bianchi Fasani et al. (2014); Gioia et al. (2010); Gori et al. (2014); Moro et al. (2012); Savelli et al. (2013)
	Carpathians (Poland, Czech Republic, Slovakia, Romania)	>113	Rotational and translational landslides, few earthflows	^{14}C	Alexandrowicz (1993); Hradecký et al. (2004, 2007); Margielewski (1997, 2001, 2006); Margielewski et al. (2010); Mindrescu et al. (2013); Pánek et al. (2013a, 2013b)
Asia	Middle East (Turkey, Iran, Israel)	>12	Rock avalanches, rockfalls, sackung-type slope deformations	^{14}C (42%), ^{10}Be (33%), OSL	Baroň et al. (2013); Ocakoglu et al. (2009); Rinat et al. (2014); Roberts and Evans (2013) ; Ryb et al. (2013)

(continued)

Table 3. (continued)

Continent	Region	Number of dated landslides[1]	Predominant type of dated landslides/comment	Dating methods used	Main references[2]
	Himalayan-Tibet orogeny (India, Pakistan, Nepal, China, Kyrgyzstan)	>55	Rockslides, rock avalanches and debris flows	^{10}Be (56%), ^{36}Cl (29%), OSL (5%), ESR, TL, ^{234}U/^{230}Th	Barnard et al. (2006); Bookhagen et al. (2005); Chen et al. (2013); Dortch et al. (2009); Hewitt et al. (2011); Sanhueza-Pino et al. (2011); Yi et al. (2006); Yuan et al. (2013)
	Hong Kong (China)	>45	Rotational and translational landslides, debris slides, debris flows, rockfalls	Majority of ^{10}Be dating complemented by ^{14}C and OSL	Sewell and Campbell (2005); Sewell et al. (2006)
	Taiwan	>11	Debris flows and rockslides	^{14}C	Goto et al. (2010); Hsieh and Chyi (2010); Hsieh et al. (2012, 2014)
	Japan	>15	Debris flows and rockslides	^{14}C	Kariya et al. (2011); Kojima et al. (2014); Xu et al. (2003); Yagi et al. (2005)
	Kamchatka (Russia)	>24	Volcanic debris avalanches	^{14}C, tephrochronology	Beethem et al. (2002); Hancox and Perrin (2009); Lacoste et al. (2009); Lee et al. (2009); Ponomareva et al. (2006)
Australasia	New Zealand	>23	Rock avalanches, translational block slides	^{14}C (87%), ^{10}Be, OSL, tephrochronology	Smith et al. (2012); Sweeney et al. (2013); Van Dissen et al. (2006); Whitehouse (1983); Wright (1998)
	Papua New Guinea (Huon Peninsula)	>26	Debris flows, debris slides, rotational landslides	^{14}C	Ota et al. (1997)
Africa	South Africa (JAR, Zambia, Malawi)	>7	Rotational landslides, earthflows, rockslides	^{14}C	Shroder (1976); Singh et al. (2008); Thomas and Murray (2001)
	Canary Islands (Spain)	>7	Volcanic debris avalanches	K-Ar dating of the pre- and post-landslide volcanic units	Boulesteix et al. (2013); Lomoschitz et al. (2008); Masson et al. (2002)

[1] Involving dated reactivations of individual landslides.
[2] Papers dealing with the dating of $\geq$3 landslides or particularly important papers with respect to their methodology or landslide size.

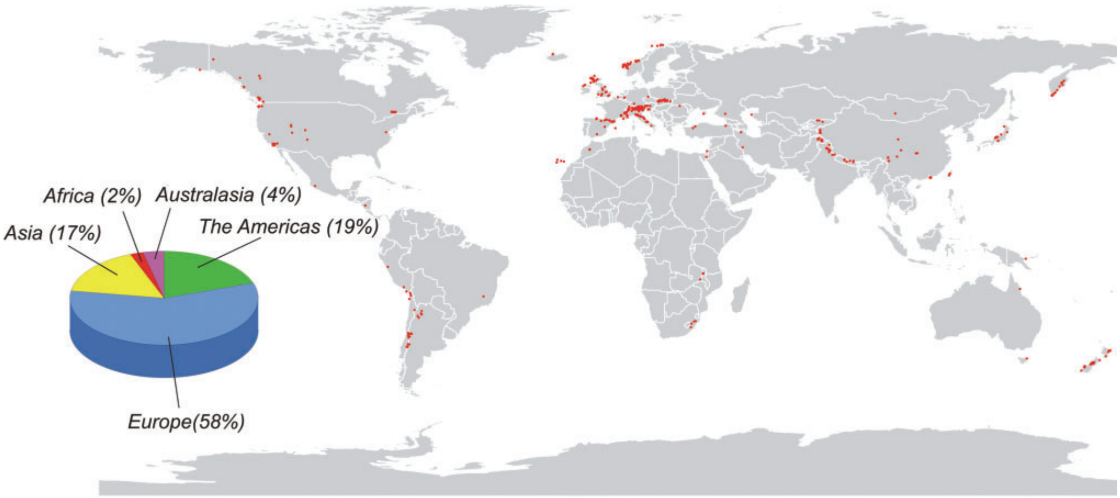

Figure 3. Global distribution of dated landslides (red dots) and their percentage on particular continents.

Negligible dating effort has been made in the mid-mountain areas of the tropics, the Great Plains of the USA, Canada, Siberia, etc. (Figure 3).

IV Major implications of dated landslides and recent research directions

Among the most important issues of the expanding data set of chronologically constrained landslides are the following: (1) new insights into the long-term evolution of mass movements; (2) the increasing credibility of landslides as paleoclimatic proxies; (3) rethinking the role of landslides in paraglacial processes; (4) the implementation of landslides in paleoseismic reconstructions; and (5) the use of landslides as indicators of past anthropogenic disturbances. The main research context of studies dealing with the timing of mass movements since 2000 is summarized in Figure 4.

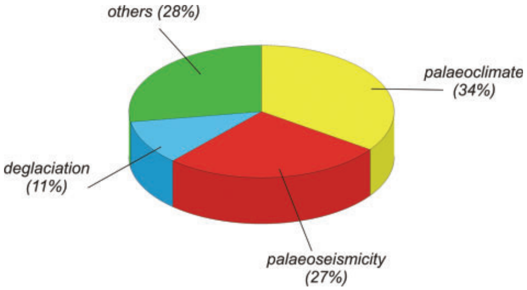

Figure 4. Main paleoenvironmental contexts of landslide dating studies (n = 205) that have been published since 2000. The category 'other' involves particular studies in which a landslide trigger is unsolved or is highly uncertain and preparatory and the triggering factors are complex.

1 Long-term evolution of landslides

The recent establishment of numerous landslide chronologies has substantially improved the understanding of the timescales in which various types of mass movements operate (Table 4). Among the most important and practical dating issues are the reconstructed instability phases of landslides, along with a definition of their recurrence interval. Some of these findings are effectively used in the evaluation of landslide risks (Friele et al. 2008; Simpson et al., 2006). A synthesis of landslide chronologies from individual case studies reveals that very large landslides ($>10^6$ m^3), in particular, frequently

Table 4. Long-term evolution of distinct types of mass movements (with dated reactivation phases) that have been recently established using various absolute dating methods.

	Examples of mass movements			
Type of mass movement	Location	Description of chronology	Methods used	Reference
Deep-seated gravitational slope deformations (mainly sackung-type deformations and lateral spreading)	Quoshadagh (Iran)	>42 ka history, several recurrences dated to ~42, 32, 25, 24, 9.6 and 8.2 ka	^{14}C+OSL/dammed-lake deposits, deformed paleosols, speleothems	Baroň et al. (2013)
	Perecalç (Pyrenees, Spain)	~45 ka history, dated deformation phases ~45.5-42.3, <17, 15.7–6 and 2–1 ka	^{14}C+OSL/deformed paleosols, colluvial and alluvial deposits excavated within trenches	Gutiérrez et al. (2012b)
	Aspen (Colorado, USA)	~11.5 ka history, dated deformation phases ~8.8, 7.2 and 3.2 ka	^{14}C/deformed paleosols excavated within trench	McCalpin and Irvine (1995)
Rotational and translational landslides	Hsiao-lin (Taiwan)	Catastrophic landslide originated on 9 August 2009. Several phases of instabilities dated to ~21.7, 14.9, 13.7 and the 12 ka preceded recent event.	^{14}C/buried organics	Hsieh et al. (2012)
	La Refaya (Pyrenees, Spain)	>12 ka history, enhanced period of rotational movement between ~12 and 8 ka followed by negligible deformation	^{14}C/rotated stratigraphic units	Gutiérrez et al. (2010)
	Girová (Carpathians, Czech Republic)	Catastrophic landslide evolved during 19–22 May 2010. Three instabilities dated to ~7.5, 1.5 and 0.6 ka BP preceded the recent event.	^{14}C/buried organics and peat bogs overlying the landslide body	Pánek et al. (2011a)
Rock avalanches and rockslides	Lake Coleridge (Canterbury, New Zealand)	Two rock avalanches from the same slope dated to ~9.7 and 0.6 ka. Third (undated) event followed immediately after the last one.	^{14}C+OSL/loess and organics buried by rock avalanche debris	Lee et al. (2009)
	Vora (Nordfjord, Norway)	Nine rock avalanche/rockfall events from the same slope dated to ~ 8, 7.1, 6.3, 5.8, 5.1, 4.8, 3.7 and 3.4 ka	^{14}C/dust layers within adjacent peat bog	Aa et al. (2007)
	Tschirgant (European Alps, Austria)	At least two rock avalanches from the same slope dated to ~3.7 and 2.5 ka	^{14}C+^{234}U/^{230}Th/buried organics and secondary speleothems within rock avalanche debris	Ostermann and Sanders (2009); Patzelt (2004) in Prager et al. (2008)

(continued)

Table 4. (continued)

	Examples of mass movements			
Type of mass movement	Location	Description of chronology	Methods used	Reference
Earthflows	Stambach (European Alps, Austria)	>11.2 ka of episodic activity preceding a major AD 1982 event, five reactivations dated to ~11.2, 8.1, 5.7, 1.9 and 1.3 ka	^{14}C/buried organics	Unkel et al. (2013)
	Corvara (Dolomites, Italy)	>9.9 ka of episodic activity; at least 13 reactivations dated to ~9.9, 9.6, 8.8, 7, 6.3, 5.3, 4.8, 4.7, 4.3, 4.2, 3, 2.6 and 2.3 ka	^{14}C/buried organics	Borgatti and Soldati (2010); Soldati et al. (2004)
	Sologno (Apennines, Italy)	>5.2 ka of episodic activity; four reactivations dated to ~5.2, 4.7, 4.3 and 2.3 ka	^{14}C/buried organics	Bertolini (2007)
Debris flows	Jinsha (SE Tibet, China)	>10.6 ka of episodic debris flow activity; four events dated to ~10.6, 8.5, 6.3 and 4.5 ka	OSL/debris flow deposits	Chen et al. (2008)
	Quebrada Tacahuay (Ilo, coastal Peru)	>11.7 ka of episodic debris flow activity; four events dated to ~11.7, 9.4, 8.8 and 5.2 ka	^{14}C/buried organics	Keefer et al. (2003)
	Sletthamn (Jotunheimen, Norway)	~8.5 ka history of multiple debris flows (32 events) from the same slope; highest frequency of events dated to 4.3–2.8 ka, the lowest was recorded between 8–7.1 ka	^{14}C/distal sheets of debris flows accumulated within adjacent peat bog	Matthews et al. (2009)

experience long and complex histories. These involve creeping movements alternating with episodic reactivations of deep-seated gravitational slope deformations on typical timescales of $\geq 10^4$ years (Carbonel et al., 2013; Gori et al., 2014; Gutiérrez et al., 2008, 2012a, 2012b; McCalpin and Hart, 2003; McCalpin and Irvine, 1995; McCalpin et al., 2011; Moro et al., 2012), up to ~10^4 years of the prolonged activity of translational and rotational landslides, earthflows and debris flows with recurrence intervals of 10^1–10^3 years (Bertolini, 2007; Bertolini et al., 2004; Borgatti and Soldati, 2010; Margielewski, 2006; Matthews et al., 2009; Pánek et al., 2013a, 2013b; Simpson et al., 2006; Soldati et al., 2004; Unkel et al., 2013) and the repeating collapse of some slopes producing successive rock avalanches and rockfalls divided typically by 10^1–10^3 years (Aa et al., 2007; Blikra et al., 2006; Bøe et al., 2004; Böhme et al., 2013; Hermanns et al., 2006; Ocakoglu et al., 2009; Ostermann and Sanders, 2009; Prager et al., 2008). Of special importance are data about the history of slope instabilities preceding recent catastrophic failures. For instance, the catastrophic August 2009 Hsiao-lin landslide in Taiwan was preceded by at least 21 ka of loose slope debris accumulation and four stages of slope instability (Hsieh et al., 2012). In a similar way, Pánek et al. (2011a) stated that the May 2010 Girová catastrophic landslide (Czech Republic) was preceded by ~7.5 ka of deep weathering of the flysch substratum and related short-travelled slope deformations. In such circumstances, dating is the only tool that can be used for backward reconstruction of mass movements for periods that are not covered by instrumental monitoring measurements.

One very important geomorphic implication of landslide dating relates to questions about the rates of decay of morphological signatures of landslides, i.e. the task influenced by climatic and topographic settings, as well as the dimensions of a particular landslide. While the morphological legacy of individual ancient landslides in arid regions may persist for periods of 10^4–10^6 years (Balescu et al. 2007; Hermanns et al., 2001; Nichols et al., 2006; Pinto et al., 2008; Sanhueza-Pino et al., 2011), it rarely exceeds 10^3 years in humid climatic conditions (Bertolini et al., 2004; González-Díez et al., 1999; Margielewski, 2006; Pánek et al., 2013a, 2013b, 2014; Prager et al., 2008). In some watersheds characterized by high erosion rates, the material of multiple landslides is completely removed even on timescales of $<10^3$ years, as was reported by Geertsema and Clague (2006). One specific example concerns mountain ranges that experienced heavy glaciation during the Late Pleistocene. In such cases, the maximum age of the landslide was usually limited by the Last Glacial Maximum (~23–19 ka) (Ballantyne et al., 2014a; Blikra et al., 2006; Prager et al., 2008) and older events are seldom extracted from only the sedimentary records (Starnberger et al., 2013). This has major implications for the length of regional landslide chronologies because those from humid temperate regions are usually shorter and biased towards younger periods of the Holocene (Pánek et al., 2013b).

2 Landslides as paleoclimatic proxies

Although hydrometeorological events are among the most obvious triggers of mass movements (Crozier, 2010), using landslides as paleoclimatic proxies has been rather problematic for a long time due to the lack of dated events and the insufficient precision of dating methods. The recent enlargement of regional landslide chronologies and new landslide dating throughout the world are challenging for correlating paleo-landslides with both broad- and short-term climatic fluctuations. Valuable data sets of dated landslides expressing major paleoclimatic changes come from distinct world regions like British Columbia (Geertsema and Schwab, 1997), the Argentine Andes (Trauth and Strecker, 1999; Trauth et al., 2000, 2003), the European Alps (Borgatti and Soldati, 2010; Borgatti et al., 2007; Prager et al., 2008; Soldati et al., 2004; Zerathe et al., 2014), the Apennines (Bertolini, 2007; Bertolini et al., 2004), the Carpathians (Margielewski, 2006) and the Himalayas (Bookhagen et al., 2005; Dortch et al., 2009).

Some of the most convincing evidence of climatically induced paleo-landslides is related to broad (millennium) scale precipitation fluctuations from territories with contrasting climatic patterns, e.g. tropical and subtropical regions that have experienced major shifts between humid and arid conditions during the Late Quaternary. Among the best examples are the contemporary arid parts of the Andes and NW Himalayas. In the eastern Andes of NW Argentina, distinct clusters of landslides (mainly rock avalanches and rockslides) were dated to two exceptionally humid periods (~40–25 and ~5–4 ka BP) that were characterized by highly variable climates (Trauth and Strecker, 1999; Trauth et al., 2000, 2003). Very similar behavior occurs in the NW Himalaya region, currently affected by heavy rainfalls only during years with exceptionally strong monsoons (Bookhagen and Burbank, 2010). Bookhagen et al. (2005) suggested that major (>0.5 km^3) rockslides originated here during two intensified monsoon phases ~29–24 and 10–4 ka BP. The validity of this assumption has been recently confirmed by numerous other dating of large rock avalanches in this territory that fit both age intervals (Dortch et al., 2009; Hewitt et al., 2011; Wang et al., 2011; Yuan et al., 2013). On the contrary, some tropical regions reveal more complex relationships between the precipitation regime and the landslide occurrence. Radiocarbon and OSL dating of landslides and debris flows in Queensland, Australia, show that they originated predominantly from arid conditions with a lack of protective vegetation cover between ~27 and 14 ka (Nott et al., 2001; Thomas et al., 2007).

One of the recent advances in landslide dating is based on growing evidence that some reconstructed landslide activity phases possibly followed major Holocene short-term climatic fluctuations; e.g. well-known ‘8.2’ and ‘4.2’ ka BP events (for the paleoclimatic background see, for example, Mayewski et al., 2004; Wanner et al., 2011). Based on radiocarbon and ^{36}Cl surface exposure dating, Ostermann et al. (2012) provided the first example of a large rock avalanche (Obernberg valley event, Eastern Alps), which could have been induced by a cold ‘8.2 ka BP event’. More convincing (and abundant) data support the correlation of multiple landslides with a global so-called ‘4.2 ka event’. Zerathe et al. (2014) recently presented the results of CRE dating for six landslides in the Maritime Alps (France) with ages between 3.7 and 4.7 ka BP and with a probability density curve centred at c. 4.2 ka BP. In addition to this evidence, Zerathe et al. (2014) suggest that numerous other dated landslides in the Alps and their surroundings chronologically approximate this age (e.g. data presented by Bertolini, 2007; Dapples et al., 2002; Delunel et al., 2010; Prager et al., 2008, 2009; Soldati et al., 2004) revealing that a 4.2 ka event could be among the most important chronological milestones for triggering rock slope failures in the European Alps.

3 Landslides and paraglacial concepts

Glacial debuttressing was long considered to be a primary factor leading to the genesis of some of the largest rock slope failures in the deglaciated mountain ranges (Cruden and Hu, 1993; Seijmonsbergen et al., 2005). However, recent studies have revealed more complex temporal relationships between rock slope stability and deglacial unloading, rock mass strength degradation, glacio-isostatic crustal uplift and climatic changes following glacial retreat (Ballantyne, 2002; Ballantyne and Stone, 2013; McColl, 2012; McColl and Davies, 2013). The main message from numerous recently dated landslides throughout formerly glaciated mountains is that the reaction of rock slopes to deglacial unloading is only rarely immediate (Cossart et al., 2008; Hippolyte et al., 2012) and that the typical delay between glacial retreat and rock slope collapse at a particular site is on the order of hundreds to thousands of years (Ballantyne et al., 2014a; Bigot-Cormier et al., 2005; Dortch et al., 2009; Fauqué et al., 2009; Hermanns and Longva, 2012; Hewitt et al., 2011; Ivy-Ochs et al., 2009; Mercier et al., 2013; Prager et al., 2008). Based on the unique chronology of 31 CRE dated rock slope failures in Scotland and NW Ireland, Ballantyne et al. (2014a) demonstrated that despite 95% of failures originating within ~5.4 ka after deglaciation, only 29% of them immediately followed the retreat of the ice sheet. Prager et al. (2008) stated that the temporal distribution of large rockslides in the European Alps is more or less uniform throughout the Late Glacial and Holocene and, therefore, rejected earlier assumptions that the major driving factor in the genesis of large rock slope failures was paraglacial debuttressing (e.g. Abele, 1969).

To sum it up, deglaciation is a crucial factor in the destabilization of mountain slopes, but rather than through direct debuttressing it influences slope stability as follows: (1) through gradual stress release and fracture propagation leading to slope collapse after several centuries or millennia (Ballantyne et al., 2013, 2014a, 2014b; Prager et al., 2008); and/or (2) through seismic activity accompanying glacio-isostatic crustal rebound, which usually occurs in the most intensive first millennia after deglaciation (Ballantyne et al., 2013, 2014a, 2014b; Mercier et al., 2013). Despite recent pronounced steps towards better understanding of the temporal behavior of landslides in deglaciated areas, more mass movement dating with a precisely determined chronology of ice retreat in various types of mountain landscapes is necessary for establishing a more universal paraglacial model of rock slope failures.

4 Paleoseismic implications of dated landslides

Because only moderate and strong earthquakes (with M_w~5–6 or larger) are able to generate major slope failures (Jibson, 2009; Keefer, 1984), some established landslide chronologies might serve as valuable paleoseismic records. However, despite the fact that earthquakes are among the most frequent triggers of mass movements, interpretation of the seismic origin of a particular fossil landslide remains a challenge. Studies focusing on landslide dating with relation to ancient earthquakes can be generally categorized as follows: (1) those using a specific spatiotemporal pattern of dated landslides as paleoseismic proxies (e.g. Aylsworth et al., 2000; Brooks, 2013; Jacoby et al., 1992; Kojima et al., 2014; Schuster et al., 1992); and (2) those attributing dated landslides to known (usually historic) seismic events (Becker and Davenport, 2003; Goto et al., 2010; Merchel et al., 2014).

The major problem with fossil landslides as paleoseismic proxies is that their earthquake trigger is often stated tentatively and, in each case, the non-seismic process could also have produced the observed features (Jibson, 2009). Such a risk can be partly overcome by careful spatiotemporal analysis of the available chronological data sets. Landslides revealing nearly identical (overlapping) ages and spatially clustered in the vicinity of active faults are considered to be the most reliable indicators of paleo-earthquake events. In this respect, studies attributing fossil landslides to seismic events vary between those where paleoseismic evidence is very strong (e.g. Aylsworth et al., 2000; Brooks, 2013; Matmon et al., 2005; Rinat et al., 2014) to those presenting paleo-earthquake(s) as only one of the possible triggers (e.g. Hermanns et al., 2001; Pánek et al., 2012; Yuan et al., 2013). The former group is represented, for example, by papers from the Ottawa valley in Quebec involving dating landslides in sensitive clays. Aylsworth et al. (2000)

provided radiocarbon dating of 15 closely situated landslides with ages clustered around ~5.12 cal ka BP. A similar tendency for temporal clustering of landslides was reported by Brooks (2013) for the stretch of the Ottawa Valley, west of Ottawa city. An extremely large landslide (~0.6 km^3) in the Quyon Valley was dated by AMS radiocarbon at 0.98–1.06 cal ka BP and excellently fits the ages of another nine landslides that are situated as much as 40 km apart. Based on the unequivocal temporal clustering and historical analogues (e.g. the earthquake-induced 5 February 1663 Colombier landslide; Cauchon-Voyer et al., 2011), these multiple reactivations of sensitive-clay landslides in the Ottawa Valley are attributed to the >M_w~6.1 earthquakes that occurred along the Western Quebec Seismic Zone (Aylsworth et al., 2000; Brooks, 2013). The second group represents numerous studies, in which the main arguments for the paleoseismic origin of landslides are their extraordinary size and the mechanism and location of the near active faults (e.g. the fault-bounded marginal slope of the mountains; Balescu et al. 2007). Many dated rock avalanches situated along the Alpine fault (New Zealand) probably originated due to major earthquakes (e.g. Barth, 2014; Chevalier et al., 2009; Dufresne et al., 2010), but verification of their seismic origin requires other independent high-resolution paleoseismological data or limiting equilibrium back analysis of slope failures (Crozier, 1992).

Due to the increasing precision of radiometric dating (especially AMS radiocarbon and CRE techniques), it has also been possible to reliably attribute specific slope failures to particular historical earthquakes, and thus to extend knowledge about their coseismic geomorphic consequences. One of the most striking examples of such an approach was provided by Becker and Davenport (2003), who dated organic macro-remains buried by numerous fallen blocks in the epicentral area of the AD 1356 Basel earthquake. The results indicate that, altogether, 11 boulders scattered throughout the area fell within a short time interval between AD 1210 and 1450, i.e. giving strong evidence that a given earthquake triggered the rockfalls (Becker and Davenport, 2003). As recently presented by Merchel et al. (2014), CRE dating also provides sufficiently precise data for the correlation of landslides with historical earthquakes. Using a large data set (n = 30) of ^{36}Cl exposure dating of bedrock surfaces and boulders, Merchel et al. (2014) correlated Veliki vrh rock avalanche (Eastern Alps, Slovenia) with a devastating January 1348 earthquake that took place along the recent Austria/Slovenia border.

5 Landslides induced by human activity

Although the direct influence of anthropogenic activity on mass movements (especially shallow landslides) is well understood (Barnard et al., 2001; Montgomery et al., 2000; Van Den Eeckhaut et al., 2007), there are very few dated landslides that can be directly attributed to historic or prehistoric anthropogenic disturbances. Some of the oldest evidence of possibly human-induced landslides was reported from Tasmania (McIntosh et al., 2009), where intensive erosion accompanying landslides and colluvial aggradation at approximately 35 ka corresponds with massive forest clearance due to human colonization. In a similar way, continuous deforestation since ~3.7 ka in the Western Swiss Alps was likely one of the factors contributing to the acceleration of earthflows dated to ~3.5 ka (Dapples et al., 2002). Other examples of possible prehistoric human-induced landslides (since the Neolithic Period) come from the Polish Western Carpathians (Margielewski, 2006). Concerning historically younger examples, Glade (2003) used sedimentary evidence in New Zealand as a record of land-use change since the 1840s (colonization by European settlers) that caused a major increase in shallow landslide frequency.

Despite the fact that documented examples of dated human-induced fossil landslides are rare, it is challenging to test the importance of prehistoric and historic human disturbances (of different magnitudes) as accelerators of various types of mass movements. Indeed, such changes are well recorded in fluvial sediments (e.g. Knox, 2006; Kukulak, 2003; Shi et al., 2002; Stacke et al., 2014). We can expect regional-scale slope destabilizations, especially in regions that have experienced major anthropogenic changes, e.g. human colonization that has taken place in formerly pristine landscapes (e.g. in some Mediterranean regions, North America). It would be a challenge to focus future landslide dating on some of these regions.

VI Concluding remarks

Mass movements, alongside fluvial and glacial processes, play a major role in sculpturing mountain areas. In such a context, it is surprising that the number of dated landslides is still low in comparison with other landscape elements. Despite this drawback, the quantity of studies related to the timing of landslides has substantially increased since the beginning of the 21st century, and it is clear that this trend will continue in the coming years. Thanks to this progress, our knowledge about the chronological framework of slope instabilities has made great strides over the last two decades. Furthermore, the introduction of new dating techniques and the improving availability, precision and effective time range of geochronological methods brings new opportunities for dating mass movements. In sum, we see the main value of the recent progress in landslide dating as follows: (1) the improvement of knowledge about the absolute timing of various landslides types operating in diverse topographic, tectonic and climatic settings; (2) the widening of the spectrum of mass movement types, which could be routinely dated; and (3) the introduction of landslides into wider paleoenvironmental reconstructions. The most scientifically sound information provides extensive and coherent regional landslide chronologies, involving landslides with similar types and magnitudes. Such data sets are becoming available for many mountain regions throughout the world, such as the high mountains of North and South America, the European Alps, the Scottish Highlands, Norway, the Carpathians, the Apennines, the Himalaya-Tibet orogeny and the Southern Alps of New Zealand. However, the majority of these regions are characterized by similar topography, tectonics and climate history, which limits our understanding of the temporal behavior of landslides into relatively narrow environmental settings. We call especially for extension of the focus of landslide dating into areas outside major mountain belts, such as continental plate interiors, hilly landscapes and coastal areas. Indeed, many of these regions (often characterized by prevailing contemporary slope stability) contain pronounced clusters of giant fossil landslides whose origins remain enigmatic.

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