Luminescence dating of hillslope deposits—A review

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A R T I C L E  I N F O

Article history:
Received 18 December 2006
Received in revised form 15 May 2007
Accepted 9 August 2008
Available online 10 March 2009

Keywords:
Optical dating
Colluvium
Geomorphology
Geoarchaeology
Climate change

A B S T R A C T

Luminescence dating determines the last exposure to light of quartz and feldspar mineral grains and thus the time a sediment was laid down. Prerequisite is that the sediment grains were sufficiently exposed to light prior to deposition. For eolian deposits this seems a fair assumption, although exceptions may well exist. For other depositional environments, light exposure prior to burial is often restricted in duration, intensity and spectral composition and may result in an age overestimation. Recent developments now allow dating of sediments that were exposed to only little light prior to deposition. The main developments are single-aliquot techniques and statistical tests that allow extraction of valid age estimates even from deposits in which bleached and unbleached grains are mixed. These developments, in combination with the fact that the great majority of sediments near the Earth’s surface are not of eolian origin, have resulted in the large interest in the luminescence dating of non-eolian deposits. Here, we review possibilities and challenges of luminescence dating of colluvial deposits. We summarize techniques for the detection and handling of insufficiently bleached sediments—a common condition in colluvial deposits. We give an overview how luminescence dating has been applied on hillslope sediments for reconstructing landscape response to climate change, to analyze past fault activity and unravel human induced soil erosion. We discuss sampling strategies and give guidelines as to which techniques are best suited to establish luminescence chronologies for colluvium.

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1. Introduction

Hillslope deposits are an important sedimentary archive for geomorphological and paleoenvironmental research. They have extensively been used for reconstructing landscape response to climate change (e.g., Hanson et al., 2004), anthropogenic induced soil erosion (e.g., Fuchs et al., 2004) and tectonic activities (e.g., Fattahi et al., 2006). Hillslope deposits often are called colluvium. Unfortunately, various definitions for colluvium are in use, and different scientific communities apply different criteria. In general, the term describes sediments that are eroded from and transported along hillslopes by running water or gravity, and that usually form wedge-shaped deposits on the foot-slope. Typically, colluvial sediments are considered to be derived from spatially diffusive processes and are distinguished from alluvial sediments, which are transported in spatially confined channels. The limited transport distance within colluvial systems reduces the complexity of such systems, allows easy delineation of the sediments’ source area and often enables straightforward identification of causes for hillslope erosion.

A prerequisite for the use of colluvial sediments as archives of paleo-processes is the knowledge about their temporal evolution. A review of techniques available for the dating slope deposits can be found in Lang et al. (1999a). To establish chronologies of late Quaternary colluviation, luminescence dating is one of the preferred dating tools as it may allow dating of the formation of the slope deposits and thus direct sediment dating. In contrast, indirect dating of slope sediments like 14C dating of organic matter, may result in age overestimation, due to frequent reworking of old carbon and long time lags before incorporation of the organic material in the sediments (Lang and Hönscheidt, 1999). The prerequisite for successful age determination in luminescence dating requires sufficient resetting of the previous luminescence signal by exposure of mineral grains to daylight. If the last process of erosion, transport and deposition does not provide sufficient bleaching of the luminescence signal (e.g., Stokes, 1999; Lian and Roberts, 2006), a remnant signal remains, that if undetected will cause an age overestimation (Fuchs and Wagner, 2005). The limited transport distance within colluvial systems that on the one hand is advantageous for geomorphology and paleoecology, on the other hand renders colluvial sediments prone to insufficient bleaching. The limited transport distance can usually be associated with only short pre-depositional light exposure. Nevertheless, in several cases colluvial sediments were successfully dated using relatively slowly bleaching thermoluminescence (TL) signals (e.g., Wintle and Catt, 1985; Forman et al., 1988). With the introduction of optical stimulated luminescence (OSL) dating by Huntley et al. (1985) and infrared stimulated OSL (IR OSL) dating of feldspars by Hütt et al. (1988), which access order of magnitude more
Hillslope erosion model after Lang and Hönscheidt (1999). The hillslope system represents a cascade system with temporary sinks. Thus, sediment may not be transported downslope in a single event, but may temporarily be stored on the slope and only later remobilized and transported to the foot-slope where it is accumulated as colluvium. The repeated cycles of erosion and sedimentation increase the probability of bleaching.
light sensitive luminescence signals, luminescence dating of colluvial sediments became more popular. Under favorable conditions OSL signals can be fully bleached within seconds of light exposure (Godfrey-Smith et al., 1988). The process leading to colluviation will not always provide such conditions and processes like attenuation of daylight by clouds and suspended particles in turbid water, or coagulation of mineral grains during transport hamper bleaching of grains. Thus, complete resetting of the OSL signal is the exception rather than the rule. In consequence, detecting and eliminating insufficient bleaching is a necessary requirement in luminescence dating of sediments (Fuchs and Wagner, 2005).

There are several possibilities for the identification of insufficient bleaching (e.g., Li, 1994; Clarke, 1996; Olley et al., 1999; Wallingga, 2002; Fuchs and Wagner, 2003). Different bleaching characteristics of different luminescence signals can also be compared: OSL and TL (Wintle et al., 1993), OSL from feldspar and quartz (e.g., Sørensen et al., 2001), OSL from coarse and fine grains (e.g., Kadereit et al., 2006a), fast and slow OSL components (e.g., Bailey et al., 1997) or different luminescence emissions (e.g., Krause et al., 1997). Most widely used are statistical analyses of equivalent dose ($D_e$) distributions obtained on single aliquots (Duller, 1991) or single grains (Lamothe et al., 1994). These approaches also allow extraction of a best estimate of the equivalent dose from an insufficiently bleached sample (e.g., Galbraith et al., 1999; Fuchs and Lang, 2001; Pepper and McKeever, 2002).

Here we review luminescence dating of colluvial sediments. We discuss techniques designed to detect and handle insufficient bleaching, present results from case studies where luminescence dating has been used on colluvial sediments, and give a perspective of their application in geomorphology and geoarchaeology.

2. Luminescence dating of colluvial sediments

The advantage of luminescence dating over other dating methods is its ability to directly date the deposition of clastic sediments (e.g., Lian and Roberts, 2006). The process resetting the luminescence ‘clock’ is the last exposure of quartz or feldspar mineral grains to daylight, a process which is likely to occur while sediments are eroded, transported and deposited. For eolian sediments, sufficient exposure to daylight to reset the luminescence signal is usually given (Hilgers et al., 2001). For colluvial sediments, complete signal resetting is often hampered by various factors.

1) Several processes are involved in sediment reworking, leading to colluviation. The important processes are soil erosion (e.g., plowing, sheet and rill erosion), mass movements (e.g., sliding, falling) and soil creep (e.g., solifluction). While these processes act on hillslope material to move it downslope, the sediment itself may move as a rigid block as in the case of sliding. Thus, in respect of daylight bleaching, only a small fraction of sediment involved in the colluviation process (e.g., only the outside layer of sediment grains on a rigid block) is exposed to daylight. If material is transported by water (e.g., sheet erosion), the intensity and spectral composition of the daylight is subdued by the usually high suspended load (Ditlefsen, 1992).

2) A large variety of hillslope materials—the source of colluvial sediments—exist, leading to a large variety in sediment characteristics, e.g., grain-size distribution, mineral composition or organic content. Thus, certain sediments tend to be transported as single mineral grains, like pure sand, others are prone to coagulation, like clay-dominated sediments. The latter often hampers sufficient zeroing of the luminescence signal, because the inner grains of an aggregate are shielded from daylight exposure (Lang and Wagner, 1996). The same may result from mineral coatings, where e.g. iron, manganese or carbonate coatings hamper daylight penetration into the mineral grains (Singhvi et al., 1986; Quickert et al., 2003).

3) The catchment morphometry and the erosion process define the sediment path, sediment travel distance and sediment sink. Due to the usually rather small catchments of colluvial systems, these parameters are rather well known and the travel distance tends to be relatively small. This decreases the probability of efficient bleaching, because the duration of light exposure is short and events may occur during unfavorable daylight conditions (e.g., transport during the night).

Despite the above mentioned shortcomings, there are many examples of successful luminescence dating of colluvium. Two factors influence this: (a) hillslope sediments are often eroded, transported and accumulated not in a single event, but temporary storage on the hillslope occurs, before a further mobilization takes place (Fig. 1; Lang and Hönscheidt, 1999). This increases the probability of exposure to daylight and thus bleaching. (b) bioturbation and mechanical processes in the soil as well as cultivation ensure that mineral grains are frequently exposed to daylight before the sediment grains are eroded and in many cases also after deposition before the sediment grains are covered through further sedimentation. According to Berger and Mahaney (1990) this process is more important for sediment bleaching than the colluvial transport itself.

Nevertheless, as in other sedimentary environments, excluding insufficient bleaching is a necessary requirement for successful luminescence dating of colluvial sediments. This is demonstrated by investigations of modern colluvial sediments, where residual luminescence signals were identified, which would result in age over-estimations of hundreds (Lu et al., 2002) or even thousands of years (Porat et al., 2001).

2.1. Detection of insufficiently bleached sediments

Recent years have seen big improvements for detecting and handling insufficient bleaching. The techniques available to detect insufficient bleaching are based on comparing different luminescence signals or the degree of bleaching of different mineral grains. Earlier studies explored the lower light sensitivity of TL compared to OSL (Fig. 2; Godfrey-Smith et al., 1988). For example Wintle et al. (1993) compare TL and IR-OSL (infrared stimulated luminescence) of the same colluvial samples from Natal/South Africa, and find that TL ages are up to 10 ka older than IR-OSL ages. However, IR-OSL ages are also overestimating the expected age, and Wintle et al. (1993) conclude that in this setting IR-OSL is only suitable for dating older colluvial deposits where the residual age is insignificant.

Various grain-size fractions may also show different degrees of bleaching. In luminescence dating, generally two different fractions are used: fine grains (4–11 µm) and coarse grains (90–200 µm). For alluvial sediments, several case studies have shown that the coarser grains seem to be better bleached than finer fractions (e.g., Olley et al., 1998; Wallingga, 2002). For colluvial sediments, there are no studies comparing coarse and fine grains of the same mineral type. Kadereit et al. (2006a) compare results of coarse grain quartz and fine grain feldspar extracted from colluvial sediments from a tell in Romania. The fine grains return significantly higher OSL ages than the coarse grains. This might also be caused by the different bleaching properties of the minerals, with quartz bleaching faster than feldspar (Fig. 2; Godfrey-Smith et al., 1988). A comparison of different minerals within a grain-size fraction of alluvial sediments confirms faster bleaching of quartz for modern fluvial sediments (Fuchs et al., 2005). If this behavior also holds for colluvial sediments has yet to be established.

Differences in the bleaching properties of different OSL components can also be utilized to detect insufficient bleaching. Initially differentially bleached signal components within an OSL shine-down curve were compared (Aitken and Xie, 1992). If $D_e$ is constant with stimulation time sufficient bleaching should have occurred. This technique was used for multiple aliquot protocols. However, it has also
been shown that the presence of such a plateau is necessary but not sufficient to decide if a sediment can successfully be OSL dated (Lang et al., 1999b). The OSL signal of quartz consists of fast-, medium-, and slow-components (Bulur, 1996; Bailey et al., 1997; Bailey, 2000), with the fast component bleaching most rapidly. Using single aliquot protocols, this is shown by Singarayer et al. (2005) for colluvial coarse grain quartz extracts from Oman, UK, and Kadereit et al. (2006a) show a similar behavior for poliminerial fine grain extracts from colluvial deposits in southwest Germany.

The introduction of single aliquot techniques (e.g., Duller, 1991; Roberts et al., 1998; Murray and Wintle, 2000) made it possible to develop alternative approaches to detect insufficient bleaching, especially in cases where sediments contain a mixture of grains bleached to various degrees (‘differential bleaching’ after Duller, 1994). Here, the differences between aliquots or single grains are used. The earlier attempts were based on comparing an aliquots’ (or single grains’) natural luminescence intensity and its $D_e$ (e.g., Li, 1994; Colls et al., 2001). The analyses of $D_e$ scatter can also be used to unravel insufficient bleaching (e.g. Clarke, 1996), if aliquots consist of a small number of grains only (Olley et al., 1999; Wallinga, 2002; Fuchs and Wagner, 2003). When plotting the $D_e$s as histograms (Fig. 3), well bleached samples show narrow and almost symmetrical distributions, whereas broad distributions are characteristic for insufficiently bleached samples. Often strongly skewed distributions are obtained when the majority of the grains were well bleached but also a number of poorly bleached grains is present (e.g., Olley et al., 1999; Thomas et al., 2005; Fuchs et al., 2007).

Unfortunately, all scatter based techniques can only be used for coarse grain separates. For fine grains the number of grains is too large ($>10^6$) and any scatter will be averaged out.

### 2.2. $D_e$ determination of insufficiently bleached sediments

Several techniques were developed to derive a true equivalent dose from a distribution of $D_e$ values in an insufficiently bleached sample. All these techniques are based on statistical analyses of $D_e$ variations and try to differentiate between insufficiently and sufficiently bleached aliquots. These approaches rely on a certain (usually large) number of $D_e$s determined on coarse grains using small aliquots or single grains. The common idea of all techniques is to identify the well bleached population towards the lower end of a $D_e$ distribution.

Techniques in use include (1) the use of the lowest 5% of a dose distribution as best $D_e$ estimate (Olley et al., 1998), (2) a sample specific threshold based on the experimental error obtained for this sample simulating well-bleached conditions (Fuchs and Lang, 2001), (3) the minimum age model (Galbraith et al., 1999) and a simplified version thereof (Juyal et al., 2006), and (4) the determination of a threshold via the leading edge technique (Lepper and McKeever, 2002).

Bailey and Arnold (2006) evaluate the different statistical approaches and show that significantly different estimates of the burial dose are obtained using the different models. Based on their results, the authors provide decision support criteria for which model it is best to choose for different types of dose distribution.

The underlying problem with these techniques is the uncertainty about the causes of a broad distribution. Besides the bleaching history, there are also other causes for $D_e$ scatter, such as microdosimetry or luminescence characteristics (e.g., Murray and Roberts, 1997; Kalchgruber et al., 2003). Thus, when insufficient bleaching is detected, a conservative approach is to determine a maximum age estimate for a deposit based on the median of all measured aliquots. Application of the statistical approaches requires knowledge of the variability in the case of well bleached samples. Using the lowermost $D_e$s may be erroneous as shown by Rodnight et al. (2006). They use the finite mixture model (Galbraith and Green, 1990) to identify and exclude low dose outliers that are measurement artifacts due to the luminescence characteristics of these aliquots.

**Fig. 2.** TL and OSL bleaching characteristics of quartz and feldspar (after Godfrey-Smith et al., 1988). The graph shows that the OSL signal is faster and more readily bleachable than the TL signal. It is also shown that under full daylight conditions quartz OSL bleaches faster than feldspar OSL.

**Fig. 3.** Frequency histograms of equivalent doses ($D_e$s) obtained on two samples of colluvial quartz extracts from Oman. Graph a.) shows a narrow distribution of a well bleached sample, Graph b.) shows a broad and skewed distribution, typical of an insufficiently bleached sample.
3. Applications in geomorphology, geoarchaeology and paleoclimate research

Even though luminescence dating of colluvium is rather challenging, results from a variety of case studies are available from all over the world. These include all climatic regions from polar to tropical, and represent a variety of applications in geomorphology, geoarchaeology and paleoenvironmental research (Table 1). Among the first who successfully applied luminescence dating to colluvial sediments were Forman et al. (1988) using TL dating techniques. Recently TL is very rarely applied in the dating of sediments, and optical methods (OSL, IR-OSL) are generally preferred.

3.1. Landscape response to past climatic change

The first report of successful optical dating of colluvial sediments is presented by Wintle et al. (1993). In this and successive papers (Botha et al., 1994; Wintle et al., 1995a,b) the authors were able to correlate sediments and soils with dryer or wetter climatic periods of the Late Quaternary in South Africa and describe in detail the complexity of slope evolution processes. First, TL and IR-OSL multiple-aliquot protocols on polyminal fine-grain extracts were used, and later also single-aliquot protocols on coarse-grain feldspar extracts. These studies provided chronologies for the deposits, but also showed that the light exposure history of individual colluvial sediments can be dramatically different. Using a single-aliquot IR-OSL protocol on coarse-grain feldspar separates, a wide range of $D_s$ values was obtained for the upper part of a colluvial sequence, whereas a much smaller range in $D_s$ was found in the lower part (Wintle et al., 1995b).

Comparison with radiocarbon age constraints showed that IR-OSL ages for the upper colluvium overestimated the burial age, whereas in the underlying colluvium—where grains were bleached more uniformly—the obtained IR-OSL ages were correct. TL results for the same samples showed that the TL-signals were not fully bleached at the time of deposition, but that the grains from the lower sediment had experienced considerably more light exposure prior to burial than the grains from the overlying unit.

Similar sediments have been studied by Clarke et al. (2003). They report IR-OSL ages as old as 100 ka obtained on coarse-grained feldspars and using a single-aliquot additive-dose protocol. IR-OSL ages in the younger units are consistent with $^{14}$C ages from soil organic matter extracted from paleosols.

In a study on colluvial deposits from Tanzania, Eriksson et al. (2000) identified two major colluvial periods. The first period of deposition took place during the late Pleistocene, probably related to climate change from dry to wet conditions. The second period of colluvial formation took place after a long phase of stability and soil formation and started ca. 900 years ago. This period of colluviation seems to be related to human activity, such as agricultural intensification, livestock keeping and iron smelting, and the associated land clearance. For age determination, an OSL single aliquot protocol was applied to the quartz coarse grain fraction. Measuring many aliquots per sample, the $D_s$ showed a large scatter which indicated insufficient bleaching. To extract sufficiently bleached aliquots, Eriksson et al. (2000) applied the minimum age model of Galbraith et al. (1999).

Table 1
Overview on luminescence dating studies of colluvial sediments.

<table>
<thead>
<tr>
<th>Task</th>
<th>Region</th>
<th>Luminescence technique</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Methodology</td>
<td>California, USA</td>
<td>TL</td>
<td>Berger and Huntley (1987)</td>
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<tr>
<td>Natal, South Africa</td>
<td>TL, IR-OSL, SA, Fsp, c</td>
<td>Wintle et al. (1993, 1995a,b)</td>
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<tr>
<td>Natal, South Africa</td>
<td>IR-OSL, SA, Fsp, c</td>
<td>Li (1994)</td>
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<tr>
<td>Germany</td>
<td>IR-OSL, MA, P, f</td>
<td>Lang and Wagner (1996)</td>
<td></td>
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<tr>
<td>Greece</td>
<td>OSL, SA, Q, c</td>
<td>Fuchs and Wagner (2003)</td>
<td></td>
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<tr>
<td>Oman</td>
<td>OSL, SA, Q, c</td>
<td>Fuchs et al. (2007)</td>
<td></td>
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<tr>
<td>Himalaya/Pakistan</td>
<td>TL, MA, P, f</td>
<td>Berger and Mahaney (1990)</td>
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<td>Mongolia</td>
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<td></td>
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<tr>
<td>Natal/South Africa</td>
<td>IR-OSL, SA, Fsp, c</td>
<td>Eriksson et al. (1999, 2000)</td>
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<tr>
<td>Wyoming, USA</td>
<td>OSL, SA, Q, c</td>
<td>Lehmkahl and Lang (2001)</td>
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<td>Vietnam</td>
<td>OSL, SA, Q, c</td>
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<td>Tasmania/Australia</td>
<td>OSL, SA, Q, c</td>
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<td>South Africa</td>
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<td>Tibet</td>
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<tr>
<td>Tanzania</td>
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<tr>
<td>Zambia</td>
<td>OSL, SA, Q, c</td>
<td>Strasser et al. (2001)</td>
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<tr>
<td>Fault activity</td>
<td>Australia</td>
<td>TL, MA, Q, c</td>
<td>Thomas and Murray (2001)</td>
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<td>Utah/USA</td>
<td>TL, MA, P, f</td>
<td>Hutton et al. (1994)</td>
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<td>Israel</td>
<td>TL, MA, P, f</td>
<td>McCalpin and Forman (1991)</td>
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<td>China</td>
<td>TL, IR-OSL, OSL, MA, SA, Q, Fsp, c</td>
<td>Porat et al. (1996, 1997, 2001)</td>
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<td>Iran</td>
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<td>Geoarchaeology/human induced soil erosion</td>
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<td>Lu et al. (2002)</td>
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<td>IR-OSL, MA, P, f</td>
<td>Fattahi et al. (2006)</td>
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<td>Germany</td>
<td>IR-OSL, MA, P, f</td>
<td>Lang and Hönscheidt (1999)</td>
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<tr>
<td>Germany</td>
<td>IR-OSL, MA, P, f</td>
<td>Lang et al. (1999b, 2003)</td>
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<tr>
<td>Germany</td>
<td>IR-OSL, MA, P, f</td>
<td>Kader et al. (2002, 2006a)</td>
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<td>Fuchs et al. (2004)</td>
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<td>Greece</td>
<td>OSL, SA, Q, c</td>
<td>Fuchs and Wagner (2005)</td>
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<tr>
<td>Romania</td>
<td>OSL, IR-OSL, MA, SA, Q, P, c, f</td>
<td>Kader et al. (2006b)</td>
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<tr>
<td>Belgium</td>
<td>OSL, SA, Q, f</td>
<td>Rommens et al. (2007)</td>
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SA: Single Aliquot; MA: Multiple Aliquot; Q: Quartz; Fsp: Feldspar; P: Polyminal; c: coarse grain; f: fine grain.
On Tasmania, Duller (2004) was investigating colluvium associated with a raised marine terrace in a relatively tectonically stable region. The raised terrace, associated with a global high sea-level stand, was OSL dated using single aliquot and single grain protocols and coarse grain quartz. Measurements on large aliquots (>1000 grains per aliquot) resulted in an age estimate of ca. 20 ka, a time when eustatic sea-level was below instead of above present sea level. Additionally, the broad $D_e$ distribution indicated insufficient bleaching. When small aliquots (ca. 200 grains per aliquot) and single grains were investigated, the variability in $D_e$ values increased and the weighted mean $D_e$ decreased. The $D_e$ histograms obtained show a tendency to more positively skewed $D_e$ distributions with a more pronounced ‘tail’ towards higher $D_e$ values when the number of grains per aliquots decreases (Fig. 4). This can be explained by the presence of poorly or unbleached grains within many grains that were bleached at deposition. For age calculation, Duller (2004) used only the well bleached grains from the lower part of the $D_e$ distribution based on single grain measurements. The estimated OSL age for the raised beach was between 5 ka and 6 ka, which fits with a global high sea-level stand in the mid-Holocene. The insufficient bleaching of the material could be explained by the re-working of the raised terrace sediments, resulting in colluviation.

3.2. Past fault activity and paleoearthquake reconstruction

The vertical displacement along a fault scarp leads to its erosional degradation, thus colluviation. The dating of these colluvial sediments enables the reconstruction of fault activity and earthquake recurrence intervals, which are important information for natural hazard assessment.

Porat et al. (1996) were the first who applied optical dating to colluvial sediments associated with fault scarp activities for estimating seismic hazards. In their studies at the Arava fault, Israel, they were able to establish an earthquake chronology with four large earthquakes ($M \geq 7$) in the period of 37 ka–14 ka and five smaller earthquakes ($M = 6.2–6.6$) in the following time until recently. Based on these data, Porat et al. (1996) derived a recurrence interval of earthquakes with a magnitude $\geq 6.2$ of ca. 4 ka. For $D_e$ determination of the colluvial sediments, coarse grain feldspar extracts were measured with a single aliquot protocol. Due to no correlation between $D_e$ and natural signal intensity (Li, 1994), the colluvial samples seemed to be sufficiently bleached. This was supported by only minor residual ages of modern colluvial sediments, showing an age of ca. 550 a. In general, the suitability of colluvial sediments for investigating fault activities at the Arava fault in southern Israel was confirmed by Porat et al. (1997). However, Porat et al. (2001) recognized a slope-face dependency for the bleaching degree of colluvial sediments, with colluvial sediments from south-facing scarps being better bleached than colluvium derived from north-facing scarps.

In a study from Xiyangfang, China, Lu et al. (2002) applied OSL and IR-OSL multiple aliquot protocols on polymineral fine grain (4–11 µm) extracts from colluvial sediments, to reconstruct the earthquake recurrence interval of the last 30 ka. Based on $D_e$ estimated from modern colluvial sediments, a residual luminescence signal with a mean $D_e$ of ca. 1.37 ± 0.28 Gy could be obtained for the IR-OSL measurements and 1.76 ± 0.13 Gy for the OSL measurements. To correct for insufficient bleaching, these values were subtracted from $D_e$ estimates of the dated samples. From the resulting OSL age estimates for paleoearthquake activities of the last 30 ka, a rough recurrence interval of ca. 7 ka could be given. However, luminescence dated paleoearthquakes could only partially be correlated to historically documented earthquakes.

Fattahi et al. (2006) report OSL dating of colluvial sediments from the Sabzevar thrust fault in northeastern Iran. They used a single aliquot regenerative-dose (SAR) protocol on quartz extracts in the grain size range of 38–63 µm and obtained narrow and symmetrical $D_e$ distributions, indicating sufficient bleaching of the colluvial sediments. The OSL ages link the fault activity to the 1052 AD Baihaq earthquake.

3.3. Past human-induced soil erosion

Next to naturally induced soil erosion due to e.g. climate change or fault activity, human impact is one of the main factors responsible for Holocene soil erosion and colluviation. The reason for this anthropogenic dominance as a factor for Holocene colluviation is related to the socio-economic change from the Paleo- and Mesolithic to the Neolithic, when humans started to build permanent settlements, to domesticate animals and to cultivate land. This change resulted in widespread woodland
clearance and associated soil erosion and colluviation. Therefore, colluvial sediments are an important archive in geoarchaeological research and have successfully been used to unravel past human activities.

Among the first who successfully dated human induced colluvial sediments derived from a loess-covered landscape in southwest Germany was Lang (1994). In this study, colluvial sediments in the vicinity of an archaeological site were investigated, applying a multiple aliquot protocol for polymineral fine grain extracts (4–11 μm), using the subtraction technique by Aitken and Xie (1992). The results showed that even for the trench fillings with a maximum sediment transport distance of 100 m, the IR-OSL signal must have been bleached during the last sediment reworking. This was proven by archaeological evidence, stratigraphic consistency and an agreement between a TL and IR-OSL age of a heated sample from a fireplace. The successful application of the IR-OSL multiple aliquot polymineral fine grain technique to loess-derived colluvium could be confirmed at several sites from the loess hills of south Germany (e.g., Kadereit et al., 2002). Lang (2003) constructed a frequency distribution of 60 IR-OSL ages from southwest Germany. Phases of increased colluviation coincide with phases of higher population density and show that the intensity of farming activities is the main trigger for soil erosion.

For timing past soil erosion, OSL performs in a superior way when compared to indirect dating techniques that rely on material incorporated in the sediments like artifacts or organic remains. In these environments, the time from when a sediment particle first entered the erosion–transport–deposition pathway until it is finally laid down at the foot-slope can be very long and reworking occurs frequently. This was shown for example by Lang and Hönscheidt (1999), where time lags of several thousand years exist between the age of an object and the age of deposition (Fig. 5).

Kadereit et al. (2006b) adopted a single aliquot regeneration protocol for IR-OSL on polymineral fine grains. In this protocol IR-stimulation time is varied to differentiate between harder-to-bleach and easier-to-bleach components. The comparison of the two enables the detection of insufficiently bleached samples. Applied to colluvial sediments from an archaeological site in southwest Germany, the single aliquot IR-OSL protocol identified insufficient bleaching, which was not possible using the multiple aliquot additive dose approach. The single aliquot dating results indicate that colluviation coincides with woodland clearance in the Bronze Age/Early Iron Age and probably was related to the construction of a Celtic rampart.

In a study in Greece, Fuchs et al. (2004) applied an OSL single aliquot protocol to the quartz coarse grain fraction for reconstructing Holocene soil erosion and to elucidate the interaction of man and environment since Neolithic times. In their study they used the statistical parameter of the coefficient of variation ν in combination with small aliquots to differentiate between sufficiently and insufficiently bleached samples (Fuchs and Wagner, 2003). Based on the calculated OSL ages from several foot-slope localities, a high-resolution chronology was established and sedimentation rates calculated (Fig. 6; Fuchs et al., 2004). Colluviation strongly fluctuated in the course of the Holocene, with a sharp increase during the Early Neolithic, the onset of agricultural activities. Further periods of increased colluviation are the Middle and Late Bronze Age, the Roman period and the period since the sixteenth century AD. The good correlation between sedimentation rate and cultural activity shows that colluviation is dominated by anthropogenic drivers. However, the first phase of colluviation occurred during a period when Neolithic human impact coincided with enhanced precipitation. Probably the combination of these factors caused the sudden increase in soil erosion with the onset of the Neolithic (Fuchs and Wagner, 2005; Fuchs, 2007).

In a comparative study from Romania, Kadereit et al. (2006a) report age estimates of colluvial sediments developed at the foot-slope of a tell mound situated in an alluvial plain. Both, polymineral fine grain and quartz coarse grain separates were extracted. Ds determination for the quartz extracts were based on the OSL regenerative single aliquot protocol (SAR) using small aliquots. Insufficient bleaching was detected and Ds calculated following Fuchs and Lang (2001). For the polymineral fine grain extracts, an IR-OSL multiple-aliquot protocol was employed. The results show that OSL ages based on the best bleached quartz Ds are significantly younger than the ages derived from the IR-OSL polymineral fine.
grains. Thus, techniques available for coarse grain quartz seem to be better suited than techniques available for the fine grain extracts. Even so, compared to independent age control, both age estimates seem to overestimate the true sedimentation age.

Fine grained quartz extracts and a SAR protocol have been used by Rommens et al. (2007) to establish the history of soil erosion and Holocene slope evolution in central Belgium. Here, the first sediment deposition occurred in the early Iron Age. The sedimentation rate increased from 2.9 ± 0.9 t ha⁻¹ a⁻¹ to 5.2 ± 1.5 t ha⁻¹ a⁻¹ during the Roman Period and further to 18.0 ± 2.0 t ha⁻¹ a⁻¹ in the Middle-Ages. The study also shows the limits of OSL dating: OSL dating of soil erosion seems to be successful only if the depositional style is of a low-magnitude high-frequency character. Then sediment grains have long residence times on the slope where they are overturned by cultivation and bioturbation and effectively bleached. In such cases, only a small (if any) residual signal has to be bleached during erosion, transport, and deposition to allow for successful OSL dating. If, on the contrary, the intensity of soil erosion increases and during high magnitude events sub-soil particles are mobilized that have not been bleached on the slope, then age overestimates occur and not even SAR based OSL techniques allow extracting the ‘true’ depositional age.

4. Conclusion and perspective

Recent developments in luminescence dating enable dating of non-eolian sediments with often limited pre-depositional daylight exposure. Here we review OSL-dating of colluvial sediments and its application in geomorphology, paleoclimate reconstruction and geoarchaeology. Colluvial sediments represent an important paleoenvironmental geoarchive and being able to establish robust chronologies for such deposits is essential. Luminescence dating studies have shown that in many environments OSL-dating of colluvium is possible despite the often short transport distances. OSL dating of colluvial sediments still represents a challenge and as for other non-eolian environments sufficient bleaching must be checked for. This can be achieved by (1) the study of the Ds distribution of small aliquots and single grains, (2) comparison of luminescence signals with different light sensitivity, (3) stratigraphic consistency of OSL age estimates, and (4) comparison of OSL-ages and independent age control. Of course, compared to independent age control, both age estimates seem to scatter even for well bleached samples (Thomas et al., 2005).

The differences in luminescence and bleaching behavior (2) demonstrate that certain signal components, mineral types and grain size fractions are favorable for colluvium dating due to their higher light sensitivity. This can also be exploited to detect insufficient bleaching by comparing luminescence ages obtained from different luminescence signals like fast and slow components of quartz (e.g., Larsen et al., 2000; Singarayer et al., 2005; Li and Li, 2006), coarse and fine grain fractions, or quartz and feldspar minerals (Kaderiet et al., 2006a). If the comparison returns the same luminescence age for each of the components, the sediment grains should have experienced sufficient bleaching to completely reset both luminescence signals. A difference in the age estimates would point towards insufficient bleaching of the component returning the higher age estimate. Unfortunately in such a case, the age estimate based on a faster bleaching component may still be an age overestimate as this signal may still contain a residual signal. Also, in the case of no-bleaching during transport, two similar age estimates should be derived, both overestimates.

Therefore, establishing a chronology for colluvial sediments should always be based on several samples and—where possible—different techniques. This will allow checking the stratigraphic consistency of the obtained results (3), and (4) comparing OSL-ages and independent age control.

To reduce possible difficulties with poor bleaching, besides a thorough sedimentological analysis, a careful geomorphic evaluation of a sampling site and its catchment is also necessary before samples are taken for luminescence dating. Taking into account the following parameters significantly reduces the occurrence of insufficient bleaching.

The transport distance of the sediments should be as large as possible, because this enhances the possibility of intermittent sediment storage on the slope and thus increases the exposure time of the sediment grains to daylight.

Locations where sediments can be deposited by high magnitude events should be avoided, because high magnitude processes provide limited daylight exposure of the sediments. Additionally, high magnitude events may incorporate sub-surface sediments with high residual luminescence.

The slope aspect and topographic shading of the sediment pathway should be taken into account, as for example south facing slopes in the northern hemisphere receive more sunlight and thus provide better bleaching conditions.

Obviously not all of these parameters can always be considered and especially the conditions at the time of deposition remain unknown. Thus, the suitability of luminescence dating should be tested for every sampling site and multi-sample, multi-technique approaches should be employed. Nevertheless, recent results are very promising and shown that in many cases colluvial sediments can successfully be dated using luminescence dating, and thus opening up colluvia as valuable gearchives for paleoenvironmental research within the last glacial–interglacial cycle.

Acknowledgments

We thank the two anonymous referees for their helpful comments.

References


