BOREAS An international journal of Quaternary research

# Luminescence dating of glacial and associated sediments: review, recommendations and future directions

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BOREAS

Fuchs, M. & Owen, L. A. 2008 (November): Luminescence dating of glacial and associated sediments: review, recommendations and future directions. *Boreas*, Vol. 37, pp. 636–659. 10.1111/j.1502-3885.2008.00052.x. ISSN 0300-9483.

Dating glacial and associated sediments is essential to provide a temporal framework for accurate reconstructions of past climatic conditions and for helping to determine the nature and magnitude of glaciation for landscape evolution studies. There are few widely applicable, accurate and precise methods available to date Quaternary landforms and sediments, despite the numerous numerical dating methods that are currently available. Furthermore, there are few methods that can be utilized for the whole of the late Quaternary (*c*. 125 kyr ago to present). Recent developments in luminescence dating, however, are providing opportunities to date a broad range of late Quaternary glacial and associated landform sediments. The application of luminescence methods requires an understanding of the nature of glacial and associated environments to select the most appropriate sediment samples for dating. Problems associated with luminescence dating of glacial sediments include insufficient bleaching, low sensitivity of quartz, and variable dose rates during the history of the sediment due to changing water content or nuclide leaching. These problems can be overcome by careful sampling and descriptions of the sampling site, testing for insufficient bleaching and modelling dose rate variability.

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The Quaternary is characterized by distinct global changes of climate conditions, with extensive glaciations (glacials) in mountainous and high to mid latitude areas during periods of reduced temperatures, lasting *c*. $10^5$ years, and significantly less glaciation (interglacials), lasting *c*. $10^4$ years, during warmer times (Grootes *et al*. 1993; Ehlers & Gibbard 2003; Jouzel *et al*. 2007). Climate conditions have also varied dramatically on decadal to millennial timescales within glacials and interglacials, forcing significant changes in the glacial system (Dansgaard *et al*. 1993; Bond & Lotti 1995; Alley *et al*. 2003; Rahmstorf 2003). Former glaciations and their demise are documented by sediments and landforms. These include sediments deposited directly by the ice (glacial), encompassing a wide variety of different types of till, and associated deposits, such as, glaciofluvial, glacioaeolian, glaciolacustrine and glacier-related mass-movement sediments. These sediments, and the landforms that they constitute, provide valuable information for palaeoenvironmental reconstruction and can be used to gain a better understanding of landscape evolution and palaeoclimate change (Kaufman *et al*. 2001; Owen *et al*. 2002a; Svendsen *et al*. 2004). The use of glacial and associated sediments and landforms as palaeoenvironmental proxy, however, requires a robust temporal framework. This can be provided by relative dating methods, such as the use of morphostratigraphy and relative weathering studies. Next to relative chronologies, numerical dating methods are of fundamental importance in establishing independent chronologies (Wagner 1998). These include the use of historical records, lichenometry, tephrochronology, varve chronologies, dendrochronology, amino acid geochronology, palaeomagnetism, and radiocarbon, luminescence, K/Ar, Ar/Ar, U-series, terrestrial cosmogenic nuclide (TCN) surface exposure and fission track dating (Brigham-Grette 1996).

The application, precision and accuracy of each of these dating methods vary considerably. Radiocarbon dating is the most widely-used numerical dating method for the Quaternary. This method, however, generally requires the existence of well-preserved organic matter within the sediment or on the landforms. Unfortunately, organic matter can be very scarce within the rather sterile and extremely active geomorphic systems associated with glacial environments. Moreover, the method is limited to the last 50 kyr because of the relatively short half-life (5730±40 yr) of $^{14}C$. The method, therefore, can only be used to define changes within the latter part of the last glacial cycle. A further limitation of radiocarbon dating is that sediments cannot be dated directly. Rather, the method defines the age of organic matter that has been incorporated into the sediment from external sources and therefore the radiocarbon age may be a significant overestimation of the true sedimentation age (Lang & Hönscheidt 1999).

The growing interest in climate change during the past few decades has seen the increased use of other numerical dating methods. These include the use of historical records and lichenometry, but these can only be applied to study the past few hundred years. Palaeomagnetism and K/Ar and Ar/Ar dating have also been applied in palaeoenvironmental studies, but

DOI 10.1111/j.1502-3885.2008.00052.x 

these are more applicable for longer timescales ($>10^4$ years) or require appropriate dateable material, which is often difficult to find. In addition, dendrochronology, U-series and amino-acid geochronology have been used in many regions, but are limited by the availability of suitable materials for dating, that is, trees, inorganic/organic carbonate deposits and organic carbonate, respectively.

During the past decade, there has been a great increase in the use of TCN surface exposure dating to define the ages of moraines (e.g. Gosse *et al.* 1995a, b; Phillips *et al.* 1996, 2000; Finkel *et al.* 2003; Owen *et al.* 2003a, b). To be accurate, the method requires stable surfaces, little or no weathering, the rock and sediment dated has not acquired TCNs due to prior exposure, and the surfaces have not been shielded from cosmic rays by sediment or snow for any significant time. These conditions are hard to achieve in glacial environments (cf. Owen *et al.* 2002b; Putkonen & Swanson 2003). Furthermore, there is considerable debate regarding the appropriate production rates and scaling models to be used when calculating ages, particularly for low latitudes and high altitudes (Gosse & Phillips 2001; Balco *et al.* 2008).

Luminescence dating, in contrast to the other dating methods, can be readily applied to most terrestrial sediments and can be used to date sediments on timescales from $10^1$ to $10^5$ years, encompassing the entire late Quaternary. Moreover, the dating method defines the timing of sedimentation, thus directly dates the sediment and in most instances landform formation, and is potentially extremely accurate (Aitken 1985; Lian & Roberts 2006). The precision of the methods is highly variable, but errors to within a few percent of the age can be achieved depending upon the nature of the sediment and the laboratory methods. Luminescence dating therefore represents one of the most potentially useful and applicable dating methods for defining the age of late Quaternary glacial and associated sediments and landforms.

Surprisingly, luminescence dating has not been applied very widely to glacial and associated sediments despite its potential usefulness and applicability, and the numerous glacial geologic studies that are being undertaken by the Quaternary community. Of note, however, are studies in high altitude regions, such as, the Himalaya (Spencer & Owen 2004), Hindukush (Kamp *et al.* 2004), the European Alps (Gemmell 1999; Bavec *et al.* 2004), the Alps of New Zealand (Preusser *et al.* 2005a), and in several mid- to high-latitude areas including Antarctica (Berger & Doran 2001; Gore *et al.* 2001), Patagonia (Glasser *et al.* 2006), North America (Berger & Eyles 1994; Lamothe *et al.* 1994) and Eurasia (Duller *et al.* 1995; Thomas *et al.* 2006; Bøe *et al.* 2007; Gemmell *et al.* 2007).

The limited use of luminescence dating probably reflects a common concern that glacial and associated sediments have not been reset by sufficient daylight exposure during the last process of sediment reworking before they were deposited. Insufficient daylight exposure results in inadequate bleaching of the luminescence signal (Aitken 1985; Lian & Roberts 2006), which, if undetected, produces an age overestimation (Duller *et al.* 1995). Most studies dealing with palaeoenvironmental reconstruction of glacial environments have therefore concentrated on dating proglacial glaciofluvial, glaciolacustrine, glaciomarine and glacioaeolian sediments, which are considered less likely to have insufficient bleaching problems than glacial sediments and ice-contact sediments. Nevertheless, there are several studies where insufficient bleaching has been studied and luminescence dating had been applied successfully (Thomas *et al.* 2006). Furthermore, recent advances in luminescence dating techniques are enabling insufficient bleaching to be detected, and the identification of the well-bleached portion of the sample to be isolated, to provide reliable ages (Duller 2006).

In this article we therefore review luminescence methods and their application for dating late Quaternary glacial and associated sediments because of their potential importance and usefulness in palaeoenvironmental and landscape evolution studies. This includes: (1) a discussion of the nature of glacial sedimentary environments pertinent to luminescence dating; (2) a summary of the various methodological and technical approaches in luminescence dating to date glacial and associated sediments, especially for the detection and handling of insufficiently bleached sediments; (3) an overview of previous work on luminescence dating of glacial and associated sediments; (4) case studies from the Himalaya, Scotland and Antarctica to demonstrate the importance of luminescence dating methods for palaeoenvironmental reconstruction; (5) sampling strategies; and (6) an outlook of future directions in luminescence dating on glacial and associated sediments.

## Glacial sedimentary environments

The glacial is the most complex of all sedimentary environments, involving processes of erosion, transportation, deposition and deformation. Most glacial sedimentary units, therefore, are highly variable and comprise sediments of all particle size ranges, notably many have bimodal or multimodal particle size distributions (diamicts/diamictons). Till, *senso stricto*, is sediment that is deposited from glacial ice, and can be deposited from under the glacier (subglacial), from within the glacier (englacial) or from the surface of the glacier (supraglacial). Till may be derived from glacial erosion and entrainment of bedrock or previously deposited sediment and entrainment of debris that has fallen, washed and/or blown on to and into the glacier.

The entrained sediment may be transported frozen within the glacial ice and on the surface, within glacial meltwater or within a deforming layer at the base of the glacier. The processes of deposition may be from direct meltout or sublimation of ice, by settling from meltwaters (subglacial, englacial or supraglacial glaciofluvial), mass movement and deformation and/or lodgement of sediment subglacially. Glacial sediments may be deposited and subsequently eroded, transported and redeposited many times. Figure 1 provides a schematic representation of the nature of the paths and deposition that glacial sediment may take. Examples of glacial landforms and their sedimentary settings to illustrate this complexity of the glacial sedimentary environment are shown in Figs 2 and 3. The complex lithofacies associations that can result from glacial and associated processes are highlighted in Fig. 4 and are discussed in more detail in Benn & Owen (2002). Benn & Evans' (1998) seminal book on glacial geology provides more details on the mechanisms and the resultant products in the plethora of glacial environments that exist throughout the world and this should be examined for more insights into glacial processes and sediments.

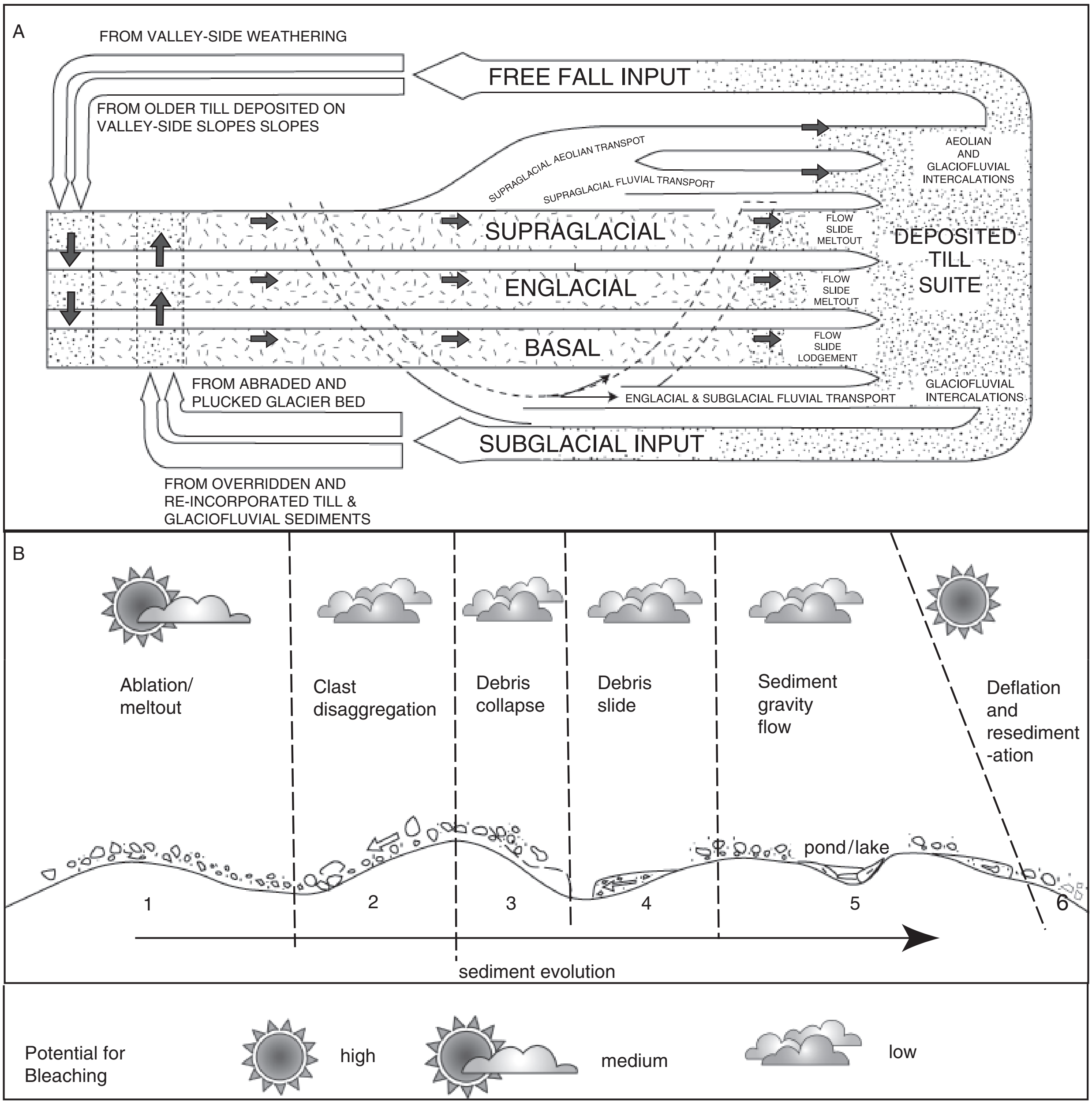


*Fig. 1.* The glacial sediment system. A. Schematic figure of the paths and deposition that glacial sediment may take (after Derbyshire 1984). B. Evolution of sediment and sedimentary processes in the supraglacial environment (adapted from Benn & Owen 2002) and potential for bleaching as supraglacial sediment evolves on the glacier surfaces (parts 1 to 6).

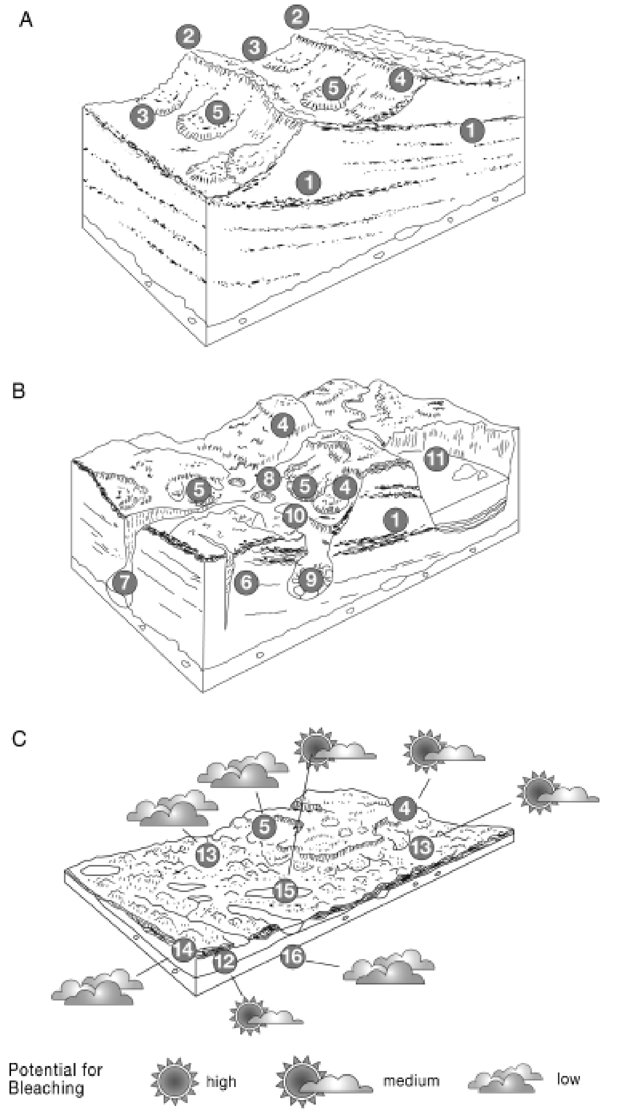


*Fig. 2.* Evolution of glacier karst on an ablating debris-mantled glacier (after Krüger 1994) and potential for beaching of the final deposits. A. Young stage. B. Mature stage. C. Old stage. 1 = Debris bands in glacier ice; 2 = ice-cored ridge; 3 = depositional trough; 4 = backwasting slope of exposed ice; 5 = debris flow; 6 = enlargement of crevasse by ice melt; 7 = subglacial conduit; 8 = sink holes; 9 = collapsed tunnel roof; 10 = enlargement of sink hole by ice melt and collapse; 11 = lake with backwasting margins; 12 = dead ice; 13 = ice-free hummocky terrain; 14 = deposits of supraglacial environments; 15 = lakes; 16 = deposits of subglacial environment.

Glaciers have a strong influence on the environments immediately bordering their margins (e.g. proglacial environments), particularly influencing the local hydrological (river and lakes) and aeolian systems that control proglacial sedimentation. We refer to sediments deposited in these environments as *associated sediments* and they comprise glaciofluvial, glaciolacustrine, glaciomarine and glacioaeolian deposits. Some of these sediments may be deposited directly on glacier ice. During times of glacier retreat as the buried ice melts, the sediments deform and sometimes are reworked by mass movement, fluvial and aeolian processes. Figure 5 illustrates some of the complexities associated with the deposition of glaciofluvial and glaciolacustrine deposits along an ice margin. When glaciers erode and deform these sediments, they often deposit new sediments, burying the earlier deposits when they advance during times of climatic deterioration. Glacial environments are important in producing vast amounts of fine sediment, which may become entrained by the wind and transported many tens to thousands of kilometres. Some of these sediments may ultimately be deposited as loess. Most loess deposits are not strictly considered glacial, although much loess owes its origin to the glacial environment. However, aeolian sediments are prevalent, common near glaciers and comprise dunes, cover sands and thin, often ephemeral, deposits of loess. The context and the variety of glacioaeolian sediments are illustrated in Fig. 6.

Understanding the nature of these glacial and associated processes is important for determining the nature of sedimentation and the context of the sedimentary deposits and landforms for determining luminescence ages. The relevance of this will become more apparent when we discuss the problems associated with dating glacial sediments and the need for good sampling strategies.

## Luminescence dating methods

Luminescence dating is a radiometric dating method that is based on the time-dependent accumulation of electrons at traps within the crystal lattice of minerals such as quartz and feldspar. Natural ionizing radiation derived from radioactive isotopes within the sediment and cosmic radiation are responsible for the gradual increase in the number of trapped electrons in the crystal lattice of the mineral over time, until a saturation level is reached. The release of the trapped electrons results in a detectable luminescence signal, the intensity of which is a measure of the amount of radiation-induced electrons, which is dependent upon the rate of ionizing radiation (dose rate) and duration of burial (Wagner 1998; Bøtter-Jensen *et al.* 2003; Lian & Roberts 2006). The electrons can be released to create the luminescence signal by stimulating the minerals with heat or light.

The type of luminescence dating is distinguished on the basis of the stimulation method, such that stimulation by heat is Thermoluminescence (TL), stimulation by visible light is optically stimulated luminescence (OSL) and stimulation by infrared light is infrared stimulated luminescence (IRSL). The most common types are OSL for quartz and IRSL for feldspar. Luminescence signals from feldspar are an order of magnitude greater than for quartz (Aitken 1998). Quartz, however, is more rapidly bleached than feldspar (Godfrey-Smith

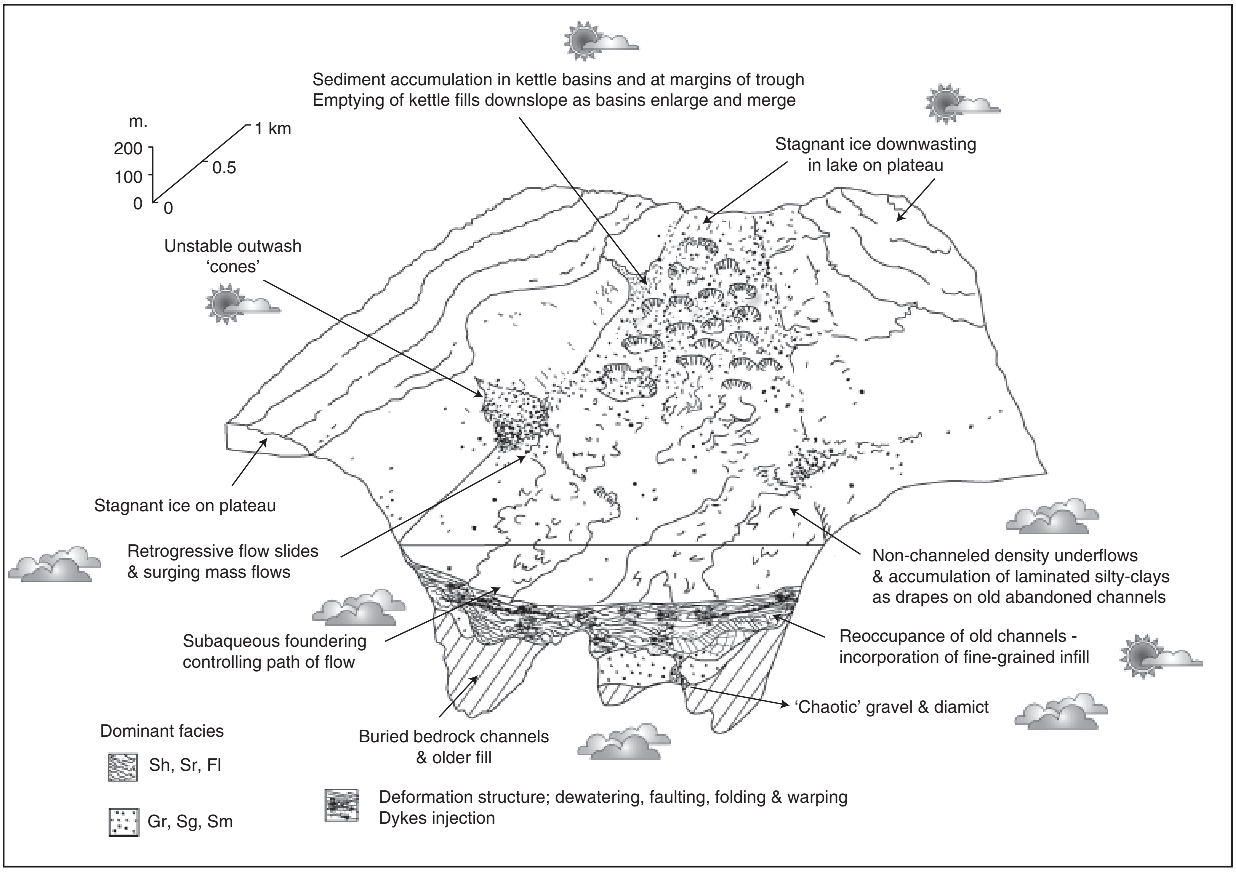


*Fig. 3*. Model for sedimentation in a supraglacial lake system in an area of moderate to high relief, based on the stratigraphy of the Fraser River valley, British Columbia, Canada (adapted from Eyles *et al.* 1987), highlighting the bleaching potential of glacial and associated sediments. The bleaching potential in this setting is generally low to moderate, with sediment being primarily bleached by reworking due to glaciofluvial, mass movement and glacioaeolian processes in the supraglacial environment.

*et al.* 1988), and does not suffer from the problem of anomalous fading, which is common to feldspar and involves the loss of trapped electrons during the sample's burial period (Aitken 1985, 1998).

TL methods were applied to dating sediment prior to the development of OSL (Huntley *et al.* 1985) and IRSL (Hütt *et al.* 1988), but it is rarely used by modern geochronologists who favour OSL and IRSL methods. A range of particle sizes can be used in determination of a luminescence age. These are usually selected to be 4–11 µm and 90–200 µm and are referred to as fine-grain and coarse-grain luminescence dating methods, respectively. Quartz and feldspar are easily separated for coarse-grain dating, but separating quartz and feldspar for fine-grain work is more complex. Commonly, polyminerals are used in fine-grain IRSL dating, where only the feldspar is stimulated by infrared. For fine-grain quartz dating, etching procedures are applied to dissolve minerals other than quartz (Berger *et al.* 1980; Fuchs *et al.* 2005).

Artificially irradiating subsamples and comparing the luminescence emitted with the natural luminescence can be used to determine the relationship between accumulated radiation energy and luminescence. Therefore, the equivalent dose ($D_e$) experienced by the grains during burial can be determined. The other quantity needed to calculate the age is the ionizing radiation dose rate ($\dot{D}$), which can be derived from direct measurements or measured concentrations of radioisotopes. The age is then derived using the equation:

$$Age = D_e/\dot{D} \tag{1}$$

The uncertainty in the age is influenced by the systematic and random errors in the $D_e$ values and possible temporal changes in the radiation flux. Determining temporal changes in the dose rate that are a consequence of changes in water content and mineral composition within the sediment is difficult. The dose rate, therefore, is generally assumed to have remained constant over time.

The age range that can be covered by luminescence dating of sediments is dependent on the unique luminescence properties of the minerals being examined and the environmental dose rate to which those minerals have been subjected. Typically, quartz can be dated back to *c*. 100–150 kyr and feldspar to *c*. 200–300 kyr,

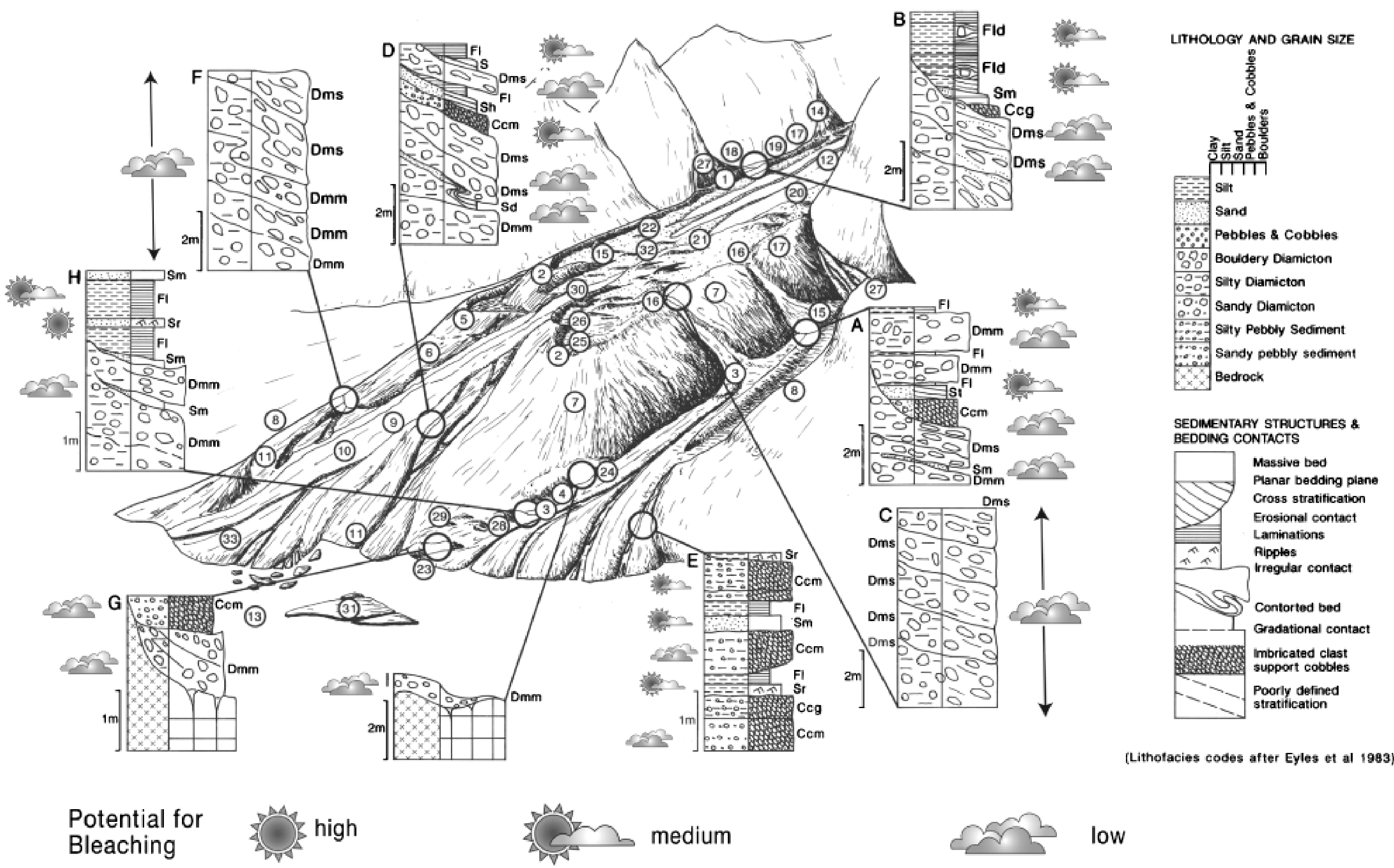


*Fig. 4.* Facies model for a debris-covered glacier with latero-frontal dump moraines and ice contact fans. This model is based on the Ghulkin Glacier (Eyles *et al.* 1983; after Owen 1994) highlighting the bleaching potential of the main glacial sediments. The bleaching potential in this setting is complex, reflecting reworking of sediments by glaciofluvial, glacioaeolian and mass-movement processes. Sediment may experience long periods ($10^3$ years) of storage between times of resedimentation, and may be transported and redeposited without being exposed to sunlight. The major landforms are listed 1–33. 1 = truncated scree; 2 = latero-terminal dump moraines; 3 = lateral outwash channels; 4 = glaciofluvial outwash fan; 5 = slide moraine; 6 = slide and debris flowcone; 7 = slide-modified lateral moraine; 8 = abandoned lateral outwash fan; 9 = meltwater channel; 10 = meltwater fan; 11 = abandoned meltwater fan; 12 = bare ice areas; 13 = trunk-valley river; 14 = debris flow; 15 = flowslide; 16 = gullied lateral moraine; 17 = lateral moraine; 18 = ablation valley lake; 19 = ablation valley; 20 = supraglacial lake; 21 = supraglacial stream; 22 = ice-contact terrace; 23 = lateral lodgement till; 24 = roche moutonée; 25 = fluted moraine; 26 = collapsed latero-frontal moraine; 27 = high-level till remnant; 28 = bedrock knoll; 29 = hummocky moraine; 30 = ice-cored moraines; 31 = river terraces; 32 = supraglacial debris; 33 = dead ice. The lithofacies associations are labelled A to I. A. Outwash channel sediments and fan associated with a lateral moraine. B. Lateral moraine and ablation valley sediments. C. Lateral moraine sediments. D. Latero-frontal moraine and glaciofluvial outwash fan sediments. E. Proglacial outwash fan sediments. F. Frontal moraine sediments. G. Bedrock, subglacial till and outwash. H. Frontal till and proglacial lacustrines. I. Exposed bedrock and subglacial till.

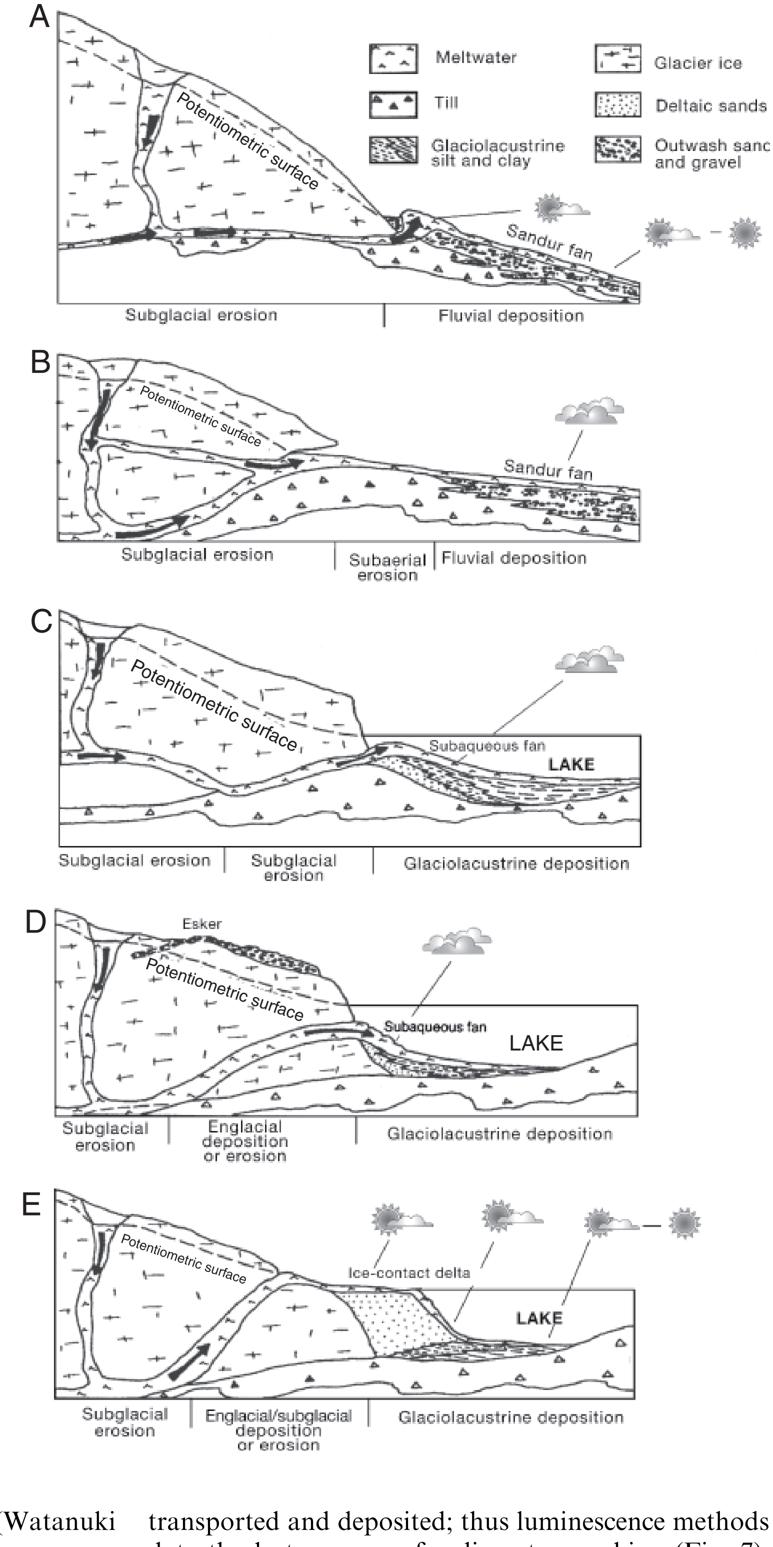


*Fig. 5.* Model of glaciofluvial and glaciolacustrine deposition based on the Malaspina Glacial, Alaska (adapted from Gustavson & Boothroyd 1987) highlighting the bleaching potential for the main glacial and sediments. The bleaching potential in this environment is generally low, which reflects rapid sedimentation in turbid streams with little exposure of sediment to sunlight.

with exceptional samples back >0.5 Myr (Watanuki *et al*. 2005; Rhodes *et al*. 2006).

Luminescence methods date the last resetting of the trapped electrons; for clastic sediments, this is the last exposure of the mineral grains to daylight (Prescott & Roberts 1997; Stokes 1999; Lian & Roberts 2006). Sediments generally experience their resetting of the luminescence 'clock' (signal) while they are eroded, transported and deposited; thus luminescence methods date the last process of sediment reworking (Fig. 7). Therefore, the prerequisite condition for dating sedimentary grains with luminescence is that they have experienced sufficient exposure to daylight to enable a complete resetting (bleaching) of the luminescence signal. Aeolian sediments, for example, are generally very well bleached (their luminescence signal is efficiently

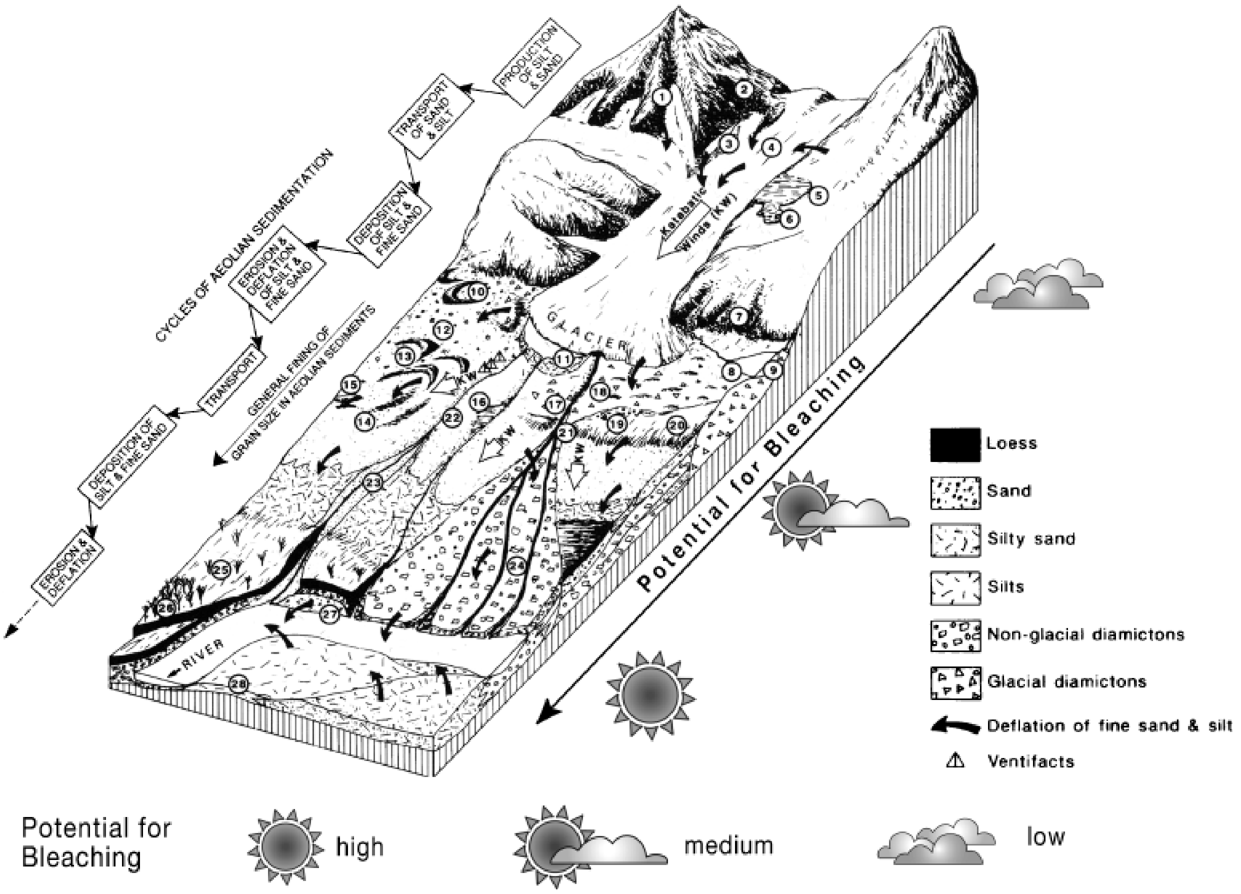


*Fig. 6*. Glacioaeolian landform–sediment association (adapted from Derbyshire & Owen 1996) highlighting the bleaching potential for the main glacial and sediments. The bleaching potential in the glacioaeolian environment is generally high and reflects prolonged subaerial exposure and reworking of sediment by deflation, with only relatively short periods of sediment storage.

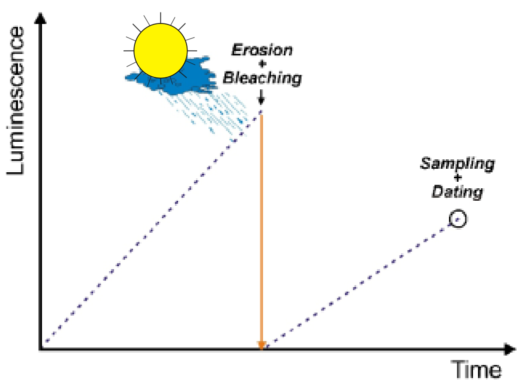


*Fig. 7*. Schematic evolution of a luminescence signal through time. During sediment burial, a latent luminescence signal builds up in the crystal lattice of the mineral. Sediment erosion and transportation resets the luminescence signal. After sediment deposition, a new luminescence signal is built up, thus the last process of sediment reworking can be dated by luminescence dating.

reset) because they experience prolonged exposure to daylight as they are transported by air currents over considerable distances (many kilometres) and for prolonged periods (1 to $10^4$ days) being continuously mixed and reworked during their transport cycle. In contrast, glacial sediments are commonly deposited very rapidly and may not be fully exposed to daylight. As such, they may not be completely bleached. In particular, much glacial sediment is transported within or at the base of the glacier and, as such, the sediments are hardly exposed to any daylight. Furthermore, a significant component of glacial sediment is produced by glacial abrasion of the transported stones, with rocks and boulders being ground by the glacier producing silt and sand-size material, which may never be exposed to daylight before being deposited.

Glacial sediments may also be deposited as a sediment package, for example, within a composite moraine, and thus the interior of these deposits was never exposed to daylight. To exacerbate the problem further, many glaciated areas are located above the polar circles, where sunlight is limited and/or absent for a significant period of the year. Sediment transportation and deposition during these periods with low or even absent sunlight will result in significant insufficient bleaching.

Even though insufficient bleaching of glacial sediments is a common problem, some glacial sediment types are more prone to this problem than others. This depends on the nature of the formation, transportation and deposition of the sediment. Deposits associated with glacial sediments, such as proglacial glaciofluvial, glaciolacustrine, glaciomarine or glacioaeolian sediments, have a higher potential to be bleached than glacial sediments such as subglacial and englacial till. Many associated sediments, however, may not be adequately bleached by sunlight. Glaciofluvial sediments, for example, may not be fully exposed to daylight because the glacial meltwaters in which they travel are turbid and the spectral composition and intensity of daylight is quickly attenuated at depth in the water column to make it ineffective in bleaching the sediment (Berger 1990; Ditlefsen 1992). This is demonstrated by investigations of modern glaciofluvial samples that exhibit residual luminescence signals, which in the geologic record would result in age overestimations (Gemmell 1997, 1999). As a consequence, glacial and associated sediments dated by luminescence have, like other sediments, to be tested for sufficient bleaching. Furthermore, it is important to undertake careful evaluation of the glacial sediments before sampling to ensure the highest potential for sampling bleached sediment. This is discussed in more detail later in this article.

### *Detection of insufficiently bleached sediments*

Significant improvements in the detection and handling of insufficient bleaching problems have been made in recent years. The techniques available to detect insufficient bleaching are based on comparing either 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. 8) (Godfrey-Smith *et al.* 1988). Berger & Doran (2001),

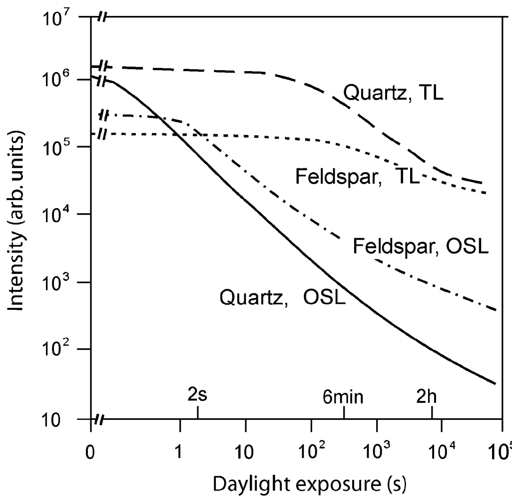


*Fig. 8.* Bleaching behaviour of quartz and feldspar exposed to sunlight for TL and OSL. OSL shows a higher sensitivity to sunlight exposure than TL, as well as quartz in comparison to feldspar (after Godfrey-Smith *et al.* 1988).

for example, compared TL and IRSL of the same glaciolacustrine samples from Lake Hoare in Antarctica and found that TL ages derived from the polymineral fine silt fraction were up to 2 kyr older than IRSL ages. The IRSL ages, however, showed an unbleached age residual of *c.* 0.6 kyr. Nevertheless, Berger & Doran (2001) concluded that for their samples these relict ages were statistically negligible for deposits older than 5 kyr. Much larger age differences between TL and IRSL age estimates were reported by Preusser (1999), who used polymineral fine-grain extracts from Swiss glaciofluvial sediments. The TL ages in this study were up to five times older than the IRSL ages. The feldspar may also have been affected by insufficient bleaching, as shown by IRSL age overestimation for some of the samples.

Different particle size fractions may also be used to help assess bleaching prior to deposition. Several case studies have shown that coarser grains seem to be better bleached than the finer fractions for alluvial sediments (e.g. Olley *et al.* 1998; Wallinga 2002). When Preusser *et al.* (2001) compared feldspar coarse grains and polymineral fine grains from glaciofluvial sediments from the Luthern Valley in Central Switzerland, the IRSL ages were within errors, and showed no difference in ages. Similar results are reported from Richards *et al.* (2000b), who determined the age of moraines in the Mount Everest area of the Khumbu Himal, Nepal. The fine and coarse grain quartz fraction in Richards *et al.*'s (2000b) study yielded OSL ages within errors.

Comparing different mineral types within a grain-size fraction, Fuchs *et al.* (2005) showed that the OSL of coarse grain quartz from fluvial sediments seems to bleach faster than the IRSL of feldspar. The faster bleaching characteristic of quartz is confirmed by studies on different glacigenic sediments from the Hunza Valley in the Karakoram Mountains, Pakistan (Spencer & Owen 2004) and from the Chitral Valley, Hindu Kush Mountains, Pakistan (Owen *et al.* 2002c). In both studies, IRSL ages derived from coarse grain feldspar measurements are significantly higher than OSL age estimates from the corresponding coarse grain quartz fraction. In a study on glacial sediments from the NW Scottish Highlands, however, Lukas *et al.* (2007) recognized no differences between IRSL ages from the coarse grain feldspar and OSL ages from the coarse grain quartz fraction of the same samples. Both mineral separates overestimated the expected Lateglacial ages by an order of magnitude. This might be due to the absence of a fast OSL component responsible for the insufficient bleaching of the sample in the case of the quartz ages.

Insufficient bleaching can also be detected by utilizing the differences in the bleaching properties of different OSL components. Aitken & Xie (1992), for example, compared the initial differentially bleached signal components within an OSL decay curve. They argued that sufficient bleaching should have occurred if the equivalent dose $D_e$ is constant over a range of stimulation times. Hütt & Jungner (1992) utilized this technique for multiple aliquot protocols, which has become known as the plateau test. Rhodes & Pownall (1994) showed, however, that the $D_e$ can be constant over a range of stimulation times, but that this is not sufficient to determine whether sediment can successfully be dated by OSL methods. Application of the plateau test based on single-aliquot protocols, defined by Bailey (2003) as the $D_e$(t) plot, seems to be more straightforward in testing for sufficient bleaching. Using the $D_e$(t) plot, Thomas *et al.* (2006) investigated glacigenic sediments from arctic Russia and concluded, due to the non-rising $D_e$(t) plot, that the investigated samples were sufficiently bleached during their last sediment reworking, which was confirmed by independent age control.

The OSL signal for quartz consists of fast, medium and slow components; with the fast component bleaching most rapidly (for more detailed information, see Bulur 1996; Bailey *et al.* 1997; Bailey 2000; Singarayer *et al.* 2005). These different components can be used to help assess whether insufficient bleaching is a problem within a sample. For example, using modern samples from various depositional environments, Singarayer *et al.* (2005) showed that the components can be resolved using linearly modulated (LM) OSL on single aliquots. Using LM OSL, Lukas *et al.* (2007) demonstrated that glacigenic sediments from Scotland are characterized by a dominance of slow bleaching medium-to-slow OSL components with only a minor fast component. They suggest that this might explain the age overestimation by an order of magnitude due to insufficient bleaching of the medium-to-slow components.

The introduction of single-aliquot regenerative (SAR) techniques to date sediments (Duller 1991; Roberts *et al.* 1998; Murray & Wintle 2000) has made it possible to develop alternative approaches for detecting insufficient bleaching. This is especially the case when sediment contains a mixture of grains that are bleached to various degrees, that is, the differential bleaching of Duller (1994). In this method, differences in $D_e$ values between aliquots or single grains are utilized to explore the likelihood that not all the grains in the sediment were totally bleached. The earliest attempts at this method used the comparison of the aliquots' (or single grains') natural luminescence intensity and its $D_e$ (Li 1994; Duller *et al.* 1995). These methods were not particularly fruitful and have been replaced by simply examining the scatter of $D_e$ values (Galbraith *et al.* 1999), particularly using small aliquots containing only a small number of grains (Olley *et al.* 1999; Wallinga 2002; Fuchs & Wagner 2003) or single grains (Thomas *et al.* 2005). When plotting the $D_e$ values as histograms (Fig. 9), the well-bleached samples are characterized by narrow and almost symmetrical normal distributions,

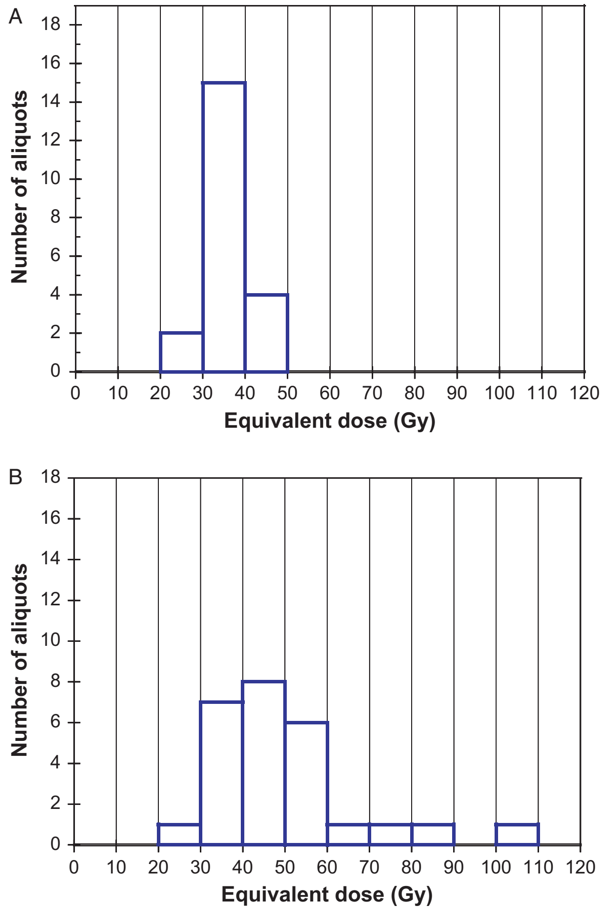


*Fig. 9.* Frequency histograms of equivalent doses (plotted at the same scale and frequency interval) obtained on single aliquots of quartz from two glaciogenic samples from the Nenana valley in Central Alaska (data from Dortch 2006). A. A relatively tight distribution indicating sufficient bleaching for a glacioaeolian sediment that overlies a till. B. A broad and skewed distribution, typical of an insufficiently bleached sample for a glaciofluvial sediment within till deposits.

whereas poorly bleached samples have a broad distribution and are skewed towards the smaller $D_e$ values (Duller 2004; Fuchs *et al.* 2007). Strongly skewed distributions reflect a small number of poorly bleached grains within a dominantly bleached sample (e.g. Olley *et al.* 1999; Thomas *et al.* 2005; Fuchs *et al.* 2007).

Bleaching characteristics of glaciofluvial sediments from Norway were examined by Bøe *et al.* (2007) using the $D_e$ distributions from small aliquots and single grains of quartz. Bøe *et al.* (2007) concluded that the symmetric shape of the $D_e$ value distributions indicated that sufficient daylight exposure and bleaching of the sediment grains had occurred during their transport. Their OSL ages were confirmed by independent age control and investigations on the resetting characteristics of modern analogues. Alexanderson & Murray (2007) also used $D_e$ distributions for glaciofluvial sediments from southern Sweden to show that symmetry was an indicator of sufficient bleaching. Fuchs *et al.*

(2007), however, argued that the shape of a $D_e$ distribution is not a sufficient criterion by which to detect insufficient bleaching and that the site-specific width of a $D_e$ distribution ($D_e$ width of the natural sample compared to the $D_e$ width of the same sample, but artificially bleached and dosed) is a more reliable parameter (Fuchs & Lang 2001; Fuchs & Wagner 2003).

Insufficient bleaching detection by examination of the scatter of $D_e$ values can only be used for coarse grain separates because it is not possible to isolate small numbers of fine grains. Also, the number of fine grains in an aliquot is typically $>10^6$ (Duller 2008) and these large numbers will average out any recognition of insufficiently bleached grains.

### *Determination of $D_e$ for insufficiently bleached sediments*

The scatter of $D_e$ values for glacial and associated sediments that have experienced insufficient bleaching makes it difficult to objectively assess the true value of $D_e$ that is appropriate to be used for the age calculation (the numerator in Equation 1). Several methods, therefore, have been developed to help derive the best $D_e$ value. These methods are based on statistical analyses of $D_e$ values, with the aim of differentiating between sufficiently and insufficiently bleached aliquots. These approaches usually rely on a large number of $D_e$ values determined on coarse grains using small aliquots or single grains. All these methods assume that the well-bleached population, and hence the most appropriate $D_e$ value, is near the lower end of the $D_e$ distribution. These methods include: (1) 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 & Lang 2001); (3) the minimum and finite age model (Galbraith & Green 1990; Galbraith & Laslett 1993; Rodnight *et al.* 2006) and a simplified version thereof (Juyal *et al.* 2006); and (4) determination of a threshold via the leading edge technique (Lepper & McKeever 2002; Woda & Fuchs 2008).

Bailey & Arnold (2006) evaluated a selection of these different statistical approaches and showed that significantly different estimates of the $D_e$ values are obtained using the different methods. Using decision support criteria, they suggested which model is most appropriate for different types of $D_e$ value distributions. The underlying problem with these methods, however, is that the uncertainty regarding the causes of a broad distribution of $D_e$ values is more complex than the bleaching history, since it may also be due to effects such as microdosimetry and luminescence characteristics (e.g. Murray & Roberts 1997; Kalchgruber *et al.* 2003). Thus, when insufficient bleaching is detected, a conservative approach is to determine a maximum age estimate for the 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. Furthermore, by using the finite mixture model of Galbraith & Green (1990) to identify and exclude low $D_e$ value outliers that are measurement artefacts due to the luminescence characteristics of individual aliquots, Rodnight *et al.* (2006) showed that using the lowermost $D_e$ values may be erroneous.

The problem of insufficient bleaching is well illustrated in Duller's (2006) study on glaciofluvial sediments from Scotland and Chile. In this study, he applied single-grain OSL methods and measured up to 3000 quartz grains per sample. Most of the samples were remarkably well bleached, but there was also insufficient bleaching in some of them. When using the finite mixture model of Galbraith & Green (1990), Duller (2006) was able to determine ages in accordance with independent dating. One of the Scottish samples was overestimated by more than 80 kyr in an earlier study by Duller *et al.* (1995), who used IRSL methods. Duller (2006, 2008) concluded that using single-grain measurement tests for insufficient bleaching is better than using single-aliquot multiple-grain measurement tests.

## Previous studies

Among the first who applied luminescence dating to glacial and associated sediments were scholars from the former Soviet Union (Morozov 1969; Shelkoplyas 1971; Troitsky *et al.* 1979; Morozov & Shelkoplyas 1980; Kajak *et al.* 1981; Arkhipov *et al.* 1982; Hütt & Smirnov 1982) using TL dating techniques. These early works are discussed in Dreimanis *et al.* (1978), Wintle & Huntley (1980) and Gemmell (1988a). Outside the former Soviet Union, Berger (1984) and Lamothe (1984) were among the first who applied TL methods to glacigenic sediments. These early studies, however, might be problematic because of the use of the less light sensitive TL signal.

With the introduction of more light-sensitive OSL and IRSL dating techniques, the problem of insufficient bleaching of glacigenic sediments seemed to be solvable. However, the early studies by Hütt & Jungner (1992), Duller (1994) and Duller *et al.* (1995) showed that even use of the more light sensitive signals frequently overestimated the sedimentation ages due to insufficient bleaching, even though results achieved by OSL and IRSL were closer to the expected ages than former TL results. The reason for age overestimation was demonstrated by Lamothe *et al.* (1994), who undertook the first single-grain IRSL measurements on feldspar grains from glacial deposits in Quebec. In Lamothe *et al.*'s (1994) study, the individually

*Table 1*. A selective overview of luminescence dating studies on glacial and associated sediments as well as studies employing luminescence dating to construct chronologies for glacial environments. Listed studies dominantly focused on methodology.

| Region | Dated sediment | Luminescence technique | Reference |
|---|---|---|---|
| Canada | Till, glaciolacustrine | TL, MA, Fsp, Q, f | Berger (1984) |
| Antarctica | Glaciolacustrine, glaciofluvial | TL, IRSL, MA, P, f | Berger & Doran (2001) |
| Canada | till | TL, MA, Q, Fsp, P, f | Berger & Huntley (1982) |
| Canada | Glaciolacustrine, glaciomarine | TL, MA, P, f | Berger (1985), Berger & Easterbrook (1993), Berger *et al.* (1987) |
| Norway | Glaciofluvial | OSL, SAR, SA, SG, Q, c | Bøe *et al.* (2007) |
| Scotland, Chile | Glaciofluvial | OSL, SA, SG, Q, c | Duller (2006) |
| Scotland | Glaciofluvial | TL, IRSL, MA, SA, Fsp, c | Duller (1994), Duller *et al.* (1995) |
| Spitsbergen | Glaciofluvial, glaciomarine | TL, MA, P, f | Forman (1988, 1990), Forman & Ennis (1992) |
| Norway | Glaciofluvial, moraine, till | TL, MA, P, f | Gemmell (1988a, b) |
| Iceland | Glaciofluvial | TL, P, f | Gemmell (1994) |
| Italy | Glaciofluvial | TL, P, f | Gemmell (1997) |
| Italy | Glaciofluvial | IRSL, SA, P, f | Gemmell (1999) |
| Greenland | Glaciolacustrine, glaciofluvial | OSL, IRSL, TL, MA, SA, Q, Fsp, c | Hansen *et al.* (1999) |
| Russia | Glaciofluvial | TL, IRSL, MA, Fsp, c | Hütt & Jungner (1992) |
| Russia | Till | TL, MA, Q, c | Hütt & Smirnov (1982) |
| Canada | Glaciofluvial, glaciomarine | TL, MA, P, f | Jennings & Forman (1992) |
| S – Germany | Glaciofluvial | OSL, IRSL, SA, Q, Fsp, c | Klasen *et al.* (2006) |
| S – Germany | Glaciolacustrine, glaciofluvial | OSL, IRSL, SA, Q, Fsp, P, c, f | Klasen *et al.* (2007) |
| Antarctica | Glaciolacustrine, glaciofluvial | IRSL, MA, Fsp, c | Krause *et al.* (1997) |
| Canada | Glaciomarine | IRSL, SA, Fsp, c | Lamothe *et al.* (1994) |
| Scotland | Till (supraglacial) | OSL, IRSL, SA, Q, Fsp, c | Lukas *et al.* (2007) |
| Switzerland | Glaciolacustrine | IRSL, SA, Fsp, f | Preusser & Degering (2007) |
| Switzerland | Glaciofluvial | IRSL, MA, P, f | Preusser (1999) |
| New Zealand | Glaciofluvial | TL, OSL, IRSL, MA, SA, P, c, f | Preusser *et al.* (2005a) |
| Switzerland | Glaciofluvial | OSL, SA, Q, c | Preusser *et al.* (2007) |
| Himalaya/Greenland | Glaciofluvial | OSL, MA, Q, c | Rhodes & Bailey (1997) |
| Himalaya | Glaciofluvial | OSL, MA, Q, c | Rhodes & Pownall (1994) |
| Himalaya, Greenland | Glaciofluvial | OSL, SA, Q, c | Rhodes (2000) |
| Siberia | Glaciofluvial | IRSL, MA, Fsp, c, f | Stauch *et al.* (2007) |
| NW-Russia/Siberia | Glaciolacustrine, glaciofluvial | OSL, SA, Q, c | Thomas *et al.* (2006) |

OSL = Optical Stimulated Luminescence; IRSL = Infrared Stimulated Luminescence; TL = Thermoluminescence; pIRSL = post-IRSL blue OSL; SA = single aliquot; SG = single grain; MA = multiple aliquot; Q = quartz; Fsp = feldspar; P = polymineral; c = coarse grain; f = fine grain.

measured single grains showed a large age scatter due to their varying bleaching history, with some grains better bleached than others. These measurements demonstrated the great potential of measurements on single grains and small single aliquots to detect insufficient bleaching and to enable extraction of the well-bleached part of a heterogeneously bleached sample (see previous section).

Tables 1 and 2 list the studies that have utilized luminescence methods to date glacial and associated sediments. Most of these studies were performed on reworked glacigenic sediments that were accumulated in the immediate vicinity of the glacier, rather than on till. The greater success for reworked sediments is due to their grains experiencing an additional cycle of erosion, transportation and deposition; this increases the probability that the sediment grains were exposed to sufficient daylight for resetting of their luminescence signal. Several studies, however, have attempted to date till directly (Troitsky *et al.* 1979; Berger & Huntley 1982; Hütt & Smirnov 1982; Berger 1984; Berger & Eyles 1994; Lian *et al.* 1999; Tsukamoto *et al.* 2002; Hebenstreit *et al.* 2006; Liu *et al.* 2006; Yang *et al.* 2006; Lukas *et al.* 2007), but most have been unsuccessful (e.g. Lukas *et al.* 2007). In many of these studies, the relationship between the tills and the associated sediment is not clear and this makes it more complex to relate any ages to the glacial cycles. Furthermore, many studies do not describe adequately the methods used in determining the luminescence ages, specifically how the authors dealt with the issue of insufficient bleaching.

## Case studies

The study areas are located all over the world, with the exception of Africa and Australia. Tables 1 and 2 provide a summary overview of the methodologies used to study glacial and associated sediments. The examples for valley glaciers are dominated by examples from the Himalaya, whereas examples for continental ice sheets are mostly from the Fennoscandian Ice Sheet. Three example areas (the Himalaya, Scotland and Antarctica) are chosen to illustrate the application of luminescence

*Table 2.* A selective overview of luminescence dating studies on glacial and associated sediments as well as studies employing luminescence dating to construct chronologies for glacial environments. Listed studies dominantly focused on application.

| Region | Dated sediment | Luminescence technique | Reference |
|---|---|---|---|
| Sweden | Glaciolacustrine, glaciofluvial | pIRSL, SA, Q, c | Alexanderson & Murray (2007) |
| Siberia | Glaciolacustrine, glaciofluvial | *Not specified* | Alexanderson *et al*. (2001) |
| Slovenia | Till, glaciolacustrine | IRSL, MA, P, f | Bavec *et al*. (2004) |
| Himalaya/Tibet | Glaciofluvial | OSL, MA, Q, c | Owen *et al*. (1997, 2001) |
| Canada | Till glaciolacustrine | TL, Ma, P, f | Berger & Eyles (1994) |
| Antarctica | Glaciolacustrine, glaciofluvial | TL, MA, P, f | Doran *et al*. (1999) |
| Scotland | Glaciolacustrine, glaciofluvial | pIRSL, SA, Q, c | Gemmell *et al*. (2007) |
| Chile | Glaciofluvial | OSL, SA, SG, Q, c | Glasser *et al*. (2006) |
| Antarctica | Glaciolacustrine, glaciofluvial, glaciomarine | OSL, MA, SA, Q, c | Gore *et al*. (2001) |
| Taiwan | Till, glaciofluvial | OSL, SA, Q, c | Hebenstreit *et al*. (2006) |
| Antarctica | Glaciofluvial | OSL, MA, Q, c | Hodgson *et al*. (2001) |
| Scandinavia | Glaciofluvial | OSL, SA, Q, c | Houmark-Nielsen & Kjær (2003) |
| NW Russia | Glaciolacustrine, g-fluvial | OSL, SA, Q, c | Houmark-Nielsen *et al*. (2001) |
| Himalaya | Glaciolacustrine | IRSL, MA; P, f | Juyal *et al*. (2004) |
| Pakistan | Glaciofluvial | OSL, SA, Q, c | Kamp *et al*. (2004) |
| Pakistan | Glaciofluvial | OSL, IRSL, Q, Fsp, c | Kamp (2001a, b) |
| Alaska | Glacioestuarine | IRSL, TL, MA, P, f | Kaufman *et al*. (1996) |
| NW Russia | Glaciolacustrine, glaciofluvial | OSL, SA, Q, c | Kjær *et al*. (2006) |
| Japan | Glaciolacustrine | OSL, SA, Q, f | Kondo *et al*. (2007) |
| Canada | Till | IRSL, MA, P, f | Lian *et al*. (1999) |
| Tibet | Till, moraine | TL, Q | Liu *et al*. (2006) |
| Venezuela | Glaciofluvial | IRSL, MA, Fsp, c | Mahaney *et al*. (2000) |
| NW Russia | Glaciolacustrine | OSL, SA, Q, c | Mangerud *et al*. (2001) |
| NW Russia | Glaciolacustrine, glaciofluvial | OSL, SA, Q, c | Mangerud *et al*. (2004) |
| Greenland | Glaciolacustrine, glaciofluvial | OSL, IRSL, TL, MA, SA, Fsp, c | Mejdahl & Funder (1994) |
| Kyrgyz | Moraine | OSL, SA, Q, c, f | Narama *et al*. (2007) |
| Pakistan | Glaciofluvial | OSL, IRSL, Q, Fsp, c | Owen *et al*. (2002c) |
| Tibet | Moraine, glaciofluvial | OSL, SA, Q, c | Owen *et al*. (2003a) |
| Himalaya | Glaciolacustrine | OSL *Otherwise not specified* | Pant *et al*. (2006) |
| Himalaya | Glaciolacustrine | IRSL, SA, Fsp, c | Phillips *et al*. (2000) |
| Switzerland | Glaciofluvial | IRSL, TL, MA, Fsp, P, c, f | Preusser *et al*. (2001) |
| Switzerland | Glaciofluvial | IRSL, TL, MA, Fsp, P, c, f | Preusser *et al*. (2003) |
| Switzerland | Glaciofluvial | pIRSL, IRSL, SA, P, f | Preusser *et al*. (2005b) |
| Estonia | Glaciofluvial | OSL, IRSL, TL, MA, Q, Fsp, | Raukas & Stankowski (2005) |
| Himalaya | Glaciofluvial | OSL, IRSL, SA, MA, Q, Fsp, c, f | Richards *et al*. (2000a, b) |
| Himalaya | Glaciofluvial | OSL, MA, Q, c | Sharma & Owen (1996) |
| Pakistan | Glaciofluvial | IRSL, SA, Q, Fsp, c | Spencer & Owen (2004) |
| Siberia | Glaciofluvial | IRSL, MA, Fsp, c, f | Stauch *et al*. (2007) |
| N Europe | Glaciolacustrine, glaciofluvial | OSL, IRSL, TL, SA, MA, Q, Fsp, P, c, f | Svendsen *et al*. (2004) |
| Spitsbergen | Till, glaciomarine | TL, MA, Q, c | Troitsky *et al*. (1979) |
| Himalaya | Till (supraglacial) | OSL, SA, Q, c | Tsukamoto *et al*. (2002) |
| NW Russia | Glaciofluvial | OSL, TL, SA, MA, Q, Fsp, c | Tveranger *et al*. (1995) |
| England | Till | TL, MA, P, f | Wintle & Catt (1985) |
| Tibet | Moraine, till | TL, MA, P, f | Yang *et al*. (2006) |

OSL = Optical Stimulated Luminescence; IRSL = Infrared Stimulated Luminescence; TL = Thermoluminescence; pIRSL = post-IRSL blue OSL; SA = single aliquot; SG = single grain; MA = multiple aliquot; Q = quartz; Fsp = feldspar: P = polymineral; c = coarse grain; f = fine grain.

dating to glacial and associated sediments in different glacial and geographic settings. Controversial examples from southern Scandinavia have been discussed by Houmark-Nielsen (2008).

### *Himalaya*

Until the early 1980s there were few numerical ages for glacial successions in the Himalaya (Röthlisberger & Geyh 1985; Benn & Owen 1998). This was mainly because organic material for standard radiocarbon dating is extremely rare in the Himalaya and when present is usually only late Holocene in age. The first major study that applied luminescence dating was undertaken by Derbyshire *et al*. (1984) in the Hunza valley of the Karakoram Mountains in Northern Pakistan. Unfortunately, no descriptions of the dating methods, other than that they were TL ages, were provided and it is not possible to assess the validity of the dating. Owen *et al*. (2002b), and Spencer & Owen (2004) undertaking $^{10}$Be terrestrial cosmogenic radionuclide surface exposure and luminescence dating, respectively, were able to confirm the TL ages cited by Derbyshire *et al.* (1984) in studies of the same glacial succession in the Hunza Valley.

The most comprehensive study using luminescence methods in the Himalaya was undertaken by Richards (1999), who examined key glacial successions in Northern Pakistan and the Khumbu Himal in Nepal (Richards *et al.* 2000a, b). The work in the Khumbu Himal is one of the best examples of the application of luminescence dating of glacial successions for any region and is definitely the best case study for the Himalaya. In their study, Richards *et al.* (2000b) dated glaciofluvial and aeolian sediments interbedded between and overlaying tills. Figure 10 shows typical graphic sedimentary logs that illustrate the types of sediments that were successfully dated. They applied multiple-aliquot methods on both coarse-grained and fine-grained quartz, feldspar and polymineral fractions. Using different methods on the same samples, they were able to reproduce ages convincingly. The ages showed that glaciers only advanced a few kilometres beyond their present positions on the southern slopes of Mt. Everest during the global Last Glacial Maximum (LGM) at about 18–22 kyr. This contrasts markedly with the extensive advances of the Northern Hemisphere ice sheets that occurred at this time. Richards *et al.* (2000b) were also able to show that glaciers advanced about a kilometre during the early Holocene (*c.* 10 kyr) and a similar distance at *c.* 1 kyr. Furthermore, they were able to successfully date a composite moraine, showing that it had formed during the advances at *c.* 10 kyr and *c.* 1 kyr.

The luminescence ages were later confirmed by Finkel *et al.* (2003), who applied $^{10}$Be terrestrial cosmogenic radionuclide surface exposure dating to the same moraines. Finkel *et al.* (2003) were also able to date additional moraines that represented two advances prior to the LGM, a Lateglacial advance and a mid-Holocene advance. In some cases, the $^{10}$Be ages were younger than the luminescence ages. This could be due to overestimation of the OSL ages due to insufficient bleaching. However, there is considerable debate regarding the correct production rates and scaling models used to calculate $^{10}$Be ages at low and high altitudes. The differences between the OSL and $^{10}$Be ages might reflect this problem. Owen *et al.* (2008) recalculated the $^{10}$Be ages using different scaling models and showed that the $^{10}$Be and luminescence ages are within errors of each other. Together with the dating from the Hunza Valley, the two dating sets provide the best defined glacial successions in the Himalaya and present a framework for examining the glacial history of the Himalayan–Tibetan orogen.

The major problem encountered by Richards *et al.* (2000a, b) was the low sensitivity of the quartz signal (Rhodes & Pownall 1994; Rhodes & Bailey 1997; Richards *et al.* 2000b; Spencer & Owen 2004). This was also a characteristic of the quartz examined by Owen *et al.* (1997) in the Lahul Himalaya of Northern India. This characteristic is probably due to limited sensitization of the quartz derived directly from young Himalayan granites, which had not undergone significant erosion–sedimentation cycles and only a limited number of bleaching–irradiation cycles, which generally enhances the luminescence characteristics of the minerals. Furthermore, Richards (2000) and Rhodes (2000) showed that thermal transfer was also a notable problem in some Himalayan samples. In addition, Richards (2000) highlighted that many of the quartz grains contained microinclusions of feldspars that swamped the OSL signal. This problem can be identified by running IRSL tests on the samples before a sample is measured.

### *Scotland*

Most of Scotland was covered by an ice sheet during the last glacial cycle (Devensian glaciation). The timing and extent of the Devensian glaciation is still under debate and reliable chronostratigraphies for key localities for glacial reconstruction have still not been fully developed. Thus, there is a strong demand on numerical dating, especially where radiocarbon dating is not applicable due to its time-range limitation or missing dateable organic material. In this respect, luminescence dating is an important dating tool for reconstructing the glacial history of Scotland.

The first attempts to date glacigenic key localities in Scotland with luminescence methods were undertaken by Duller (1994) and Duller *et al.* (1995). In their study sites in NE Scotland, glaciofluvial sediments were dated based on a combined technique of multiple-aliquot TL and IRSL measurements of coarse-grain feldspar and on single-aliquot IRSL measurements from large aliquots (*c.* 1000 grains per aliquot). The scatter in $D_e$ with their luminescence characteristics was used to investigate the glacigenic samples for insufficient bleaching. All the samples showed indications of inadequate bleaching, even though the age for one sample was in good agreement with the radiocarbon ages on a peat layer within the sediment. Reliable $D_e$ values could not be determined for the other samples that were associated with the radiocarbon-dated peat layers used as an independent age control. Moreover, due to $D_e$ overestimation, only maximum luminescence ages could be determined. For this reason, Duller *et al.* (1995) came to the conclusion that glacigenic sediments, even a few kilometres away from the ice front, are unlikely to be dated successfully by luminescence techniques.

Duller (2006) revised this view when he successfully dated two samples (MC and BHH) from Scotland using quartz single-grain SAR techniques (Duller 2006). In

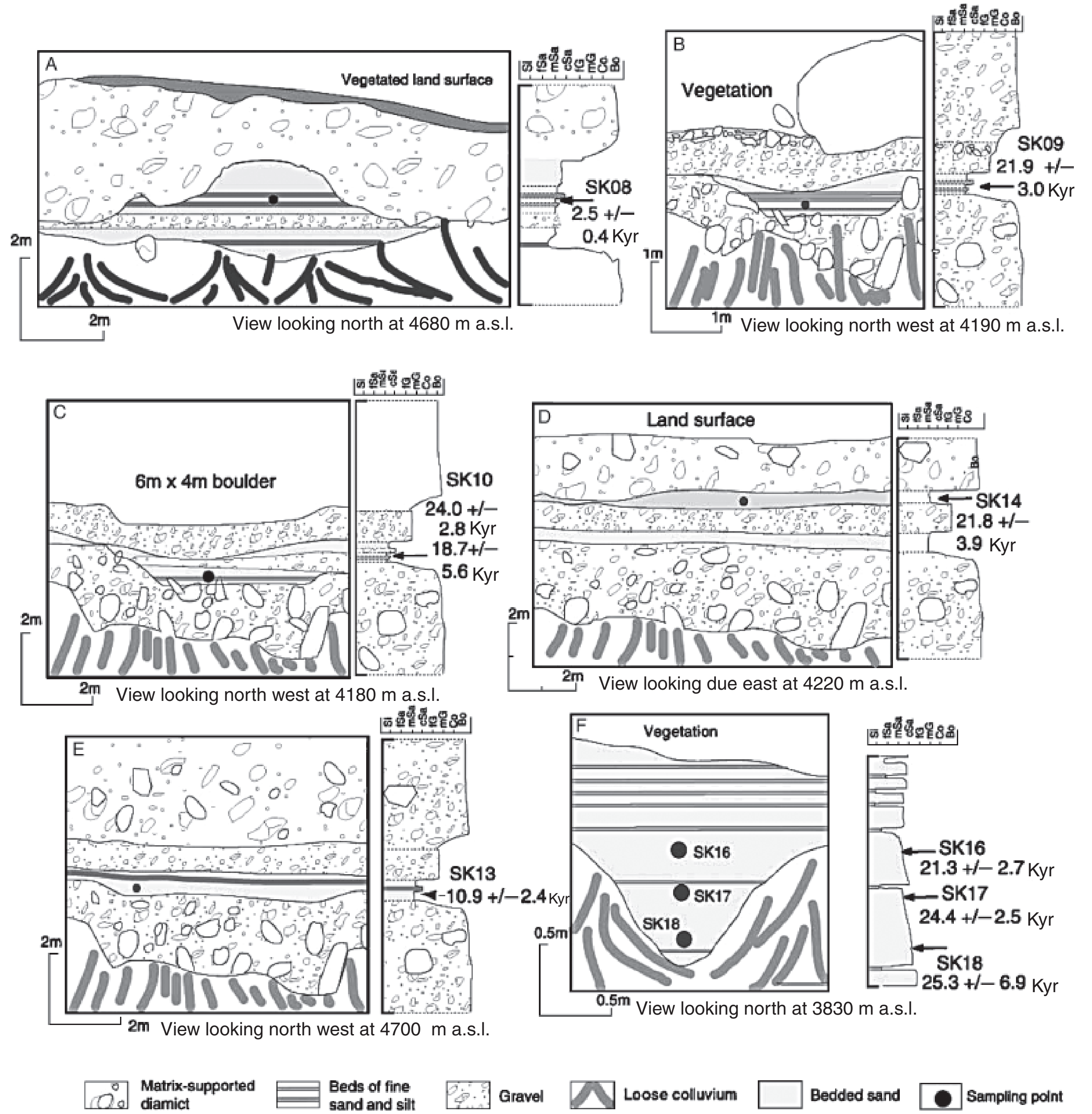


*Fig. 10*. Lateral and vertical graphic sedimentary logs showing the typical sediments and lithofacies association for glacial and associated sediments dated by Richards *et al.* (2000a) in the Khumbu Himal (Eyles *et al.* 1983). A. The sediment sampled was deposited in a shallow (*c.* 1 m deep) braided channel that formed in a supraglacial environment as river discharges fell from high to low flows. B. The sampled planar-bedded sands were deposited as a channel fill within a supraglacial stream that was *c.* 20 cm deep and *c.* 2 m wide. C. The sampled sediments were interpreted as glaciofluvial in origin and were deposited within a supraglacial braided stream that was *c.* 40 cm deep and 5 m wide. D. The sampled sediments were interpreted as glaciofluvial materials deposited in a supraglacial environment as fills in braided channels that were *c.* 30–40 cm deep and *c.* 5 m wide. These channels formed as stream discharges fell from high to low flows before the stream was eventually abandoned. E. The sampled sediment was collected from within the intercalated sands, which were interpreted as glaciofluvial sediments filling decimetre-deep and metre-wide, braided channels that are sandwiched between debrisflow deposits. These channels formed in a supraglacial environment. F. The deposits were interpreted as the products of low-density underflows (turbidites) deposited in a pond or small lake. Particle sizes are indicated on the graphic sedimentary logs (sl = silt; fSa = fine sand; mSa = medium sand; cSa = coarse sand; fG = fine gravel; mG = medium gravel; Co = cobbles; Bo = boulders and/or diamict).

an earlier study (Duller *et al.* 1995), age estimates based on IRSL single-aliquot measurements of large aliquots (*c.* 1000 grains) were 108±13 kyr and 21.3±4.6 kyr for samples MC and BHH, respectively. These earlier IRSL ages overestimated the expected ages in the case of sample MC by at least a factor of 5. The very large spread of $D_e$ values for the new single-grain quartz OSL measurements, involving measurements of 2200 (MC) and 3000 (BHH) grains per sample, show clearly that the samples were inadequately bleached. Based on the finite mixture model (Galbraith & Green 1990), age estimates of 17.3±1.5 kyr (MC) and 10.8±1.0 kyr (BHH) were calculated; these are consistent with independent age control provided by radiocarbon dating of peat layers. Duller's (2006) study shows that single-grain measurement is a useful technique for extracting the well-bleached component of the $D_e$ distribution, hence enabling a correct luminescence age to be calculated for glacigenic sediments.

### *Antarctica*

Several ice-free areas that contain freshwater lakes are situated along the coastal zone of East Antarctica. These polar oases contain important geomorphological evidence of past glacial conditions, which can help in determining the timing and extent of former glaciation. In addition, the freshwater lakes provide valuable sediment archives that can be used for palaeoenvironmental and palaeoclimate reconstruction. Several studies have shown that radiocarbon dating of Antarctic lacustrine sediments is problematic and often results in overestimates of the true age of the deposit because of reservoir effects due to the upwelling of old deep ocean waters and the melting of old glacial ice (Doran *et al.* 1999). Furthermore, many Antarctic deposits are very old and are beyond the radiocarbon dating range. Luminescence dating is potentially a powerful tool for dating Antarctic sediments, but insufficient bleaching (as discussed above) is a major problem.

Basic luminescence studies on lacustrine sediments from the Schirmacher Oasis in East Antarctica were undertaken by Krause *et al.* (1997), who investigated the bleaching characteristics using a range of emissions from coarse-grain plagioclase feldspars using IRSL. They showed that the luminescence signal from the yellow emission (560 nm) bleaches fastest with 95% signal reduction after 20 s. Using this fast bleaching emission for the $D_e$ calculation, the resulting luminescence ages were younger than those obtained using the slower bleaching emissions, the difference possibly being due to an unbleached residual signal.

Berger & Doran (2001) studied lacustrine sediments from Lake Hoare in the McMurdo Dry Valley region to assess the suitability for luminescence dating. They argued that due to the long polar darkness and the low angle of solar radiation, sediments from polar regions are prone to insufficient bleaching. Furthermore, Berger & Doran (2001) and Doran *et al.* (1999) examined recently deposited sediments from two input streams of Lake Hoare to assess this in more detail. They showed that the TL signal was reset for fine grain material from one distal flowing stream, and thus that Antarctic sediments can be adequately bleached under certain conditions, though not always. The faster bleaching IRSL signal, therefore, was used to calculate age–depth profiles for the lacustrine sediments in Lake Hoare, and showed significant younger IRSL ages than TL ages. A slight overestimation of $<600$ yr compared to recently deposited sediments, however, was also detected for the IRSL ages, but this is statistically negligible for deposits older than 5 kyr.

Studies in Antarctica, therefore, show that it is possible to date Antarctic sediments with luminescence. This could help to answer key questions such as whether polar oases in Antarctica were ice-free during the LGM. In the study by Gore *et al.* (2001) in East Antarctica, luminescence ages derived from OSL quartz coarse grain measurements showed a retreat of the glacier from the Bunger Hills at *c.* 30 kyr or even 40 kyr. At the LGM, most of this area was ice-free. Furthermore, Krause *et al.* (1997) showed that the Schirmacher Oasis in East Antarctica was ice-free at the LGM by dating lacustrine sediments using coarse-grain plagioclase IRSL, and Hodgson *et al.* (2001), using quartz coarse-grain OSL methods, showed that parts of Broknes at the Larsemann Hills in East Antarctica were also ice-free since at least 40 kyr,.

## Sampling strategies

Previous work has shown that luminescence dating of glacial and associated sediments has been undertaken with varying success. This is generally related to the bleaching history of the studied sediments, with some sediment types being better bleached than others. Most studies, therefore, were not undertaken on till, but concentrated on glaciofluvial or glaciolacustrine sediments, which experienced an additional cycle of sediment reworking. This additional cycle of erosion–transportation–deposition exposes the grains to additional daylight, thus increasing the likelihood that bleaching and resetting of the former sediments' luminescence signal would be effective. Figure 1A illustrates these pathways and highlights the potential for bleaching of supraglacial sediment, while Fig. 1B highlights supraglacial processes that modify supraglacial sediment and which have the potential to expose sediment to sunlight. The effectiveness of luminescence signal resetting is dependent on the intensity and duration of daylight exposure and therefore related to the geomorphic process responsible for sediment reworking. Thus, a geomorphological understanding of the glacial environment and its deposits is required to identify sediments and their associated geomorphological process with the maximum likelihood of sufficient daylight exposure. Figures 1 to 6 highlight the bleaching potential for different glacial and associated environments and sediments and Table 3 summarizes the sediment types, their bleaching potential and possible dose rate

*Table 3.* Glacial and associated sediments and their general suitability for luminescence dating. Bleaching probability increases with transport distance and repeated resedimentation. Dose-rate variability is a function of the mineralogical homogeneity and water content changes.

| Environment | Sediment type | Dominant particle size | Bleaching probability | Dose-rate variability |
|---|---|---|---|---|
| Glacial | Supraglacial meltout till | Diamict (silt – boulder) | Low | High - moderate |
| | Supraglacial debris flow | Diamict (silt – boulder) | Low - no bleaching | High - moderate |
| | Englacial meltout till | Diamict (silt – boulder) | Low - no bleaching | High - moderate |
| | Subglacial meltout till | Diamict (clay – boulder) | Low - no bleaching | High - moderate |
| | Deformation till | Diamict (clay – boulder) | Low - no bleaching | High - moderate |
| | Lodgement till | Diamict (clay – boulder) | Low - no bleaching | High - moderate |
| Glaciofluvial | Channel fill sediment | Sand - gravel | Low - moderate | Moderate |
| | Point bar sediments | Sand - gravel | Low - moderate | Moderate |
| | Slack water/overbank sediments | Clay - silt | Moderate | Moderate |
| | Crevasse splays | Clay - silt - sand | Moderate | Moderate |
| Glaciolacustrine | Lacustrine sediment | Silt - clay | Moderate | High |
| | Littoral sediments | Sand | High | Moderate |
| | Deltaic sediments | Silt - sand - gravel | Moderate | Moderate |
| Glaciomarine | Proximal glaciomarine sediments | Clay - silt - sand or diamict | Low - moderate | High |
| | Distal glaciomarine sediments | Clay - silt or diamict | Low - moderate | High |
| | Deltaic sediments | Silt - sand - gravel | Low - moderate | Moderate |
| | Turbidites | Silt - sand - gravel | Low - no bleaching | High |
| | Littoral sediments | Sand | High | Moderate |
| Glacioaeolian | Coversands/dunes | Sand | High | Low |
| | Loess | Silt | High | Low |

uncertainty. The identification of appropriate sediments for luminescence dating, therefore, represents the first important, and often neglected, step in obtaining reliable luminescence ages. The following list of recommendations should be considered before and during sediment sampling for luminescence dating and these build on the suggestions of Richards (2000) and Benn & Owen (2002):

(1) For the best achievable luminescence signal resetting, each mineral grain has to be exposed to daylight. Transportation distance generally enhances the duration of daylight exposure (Forman 1988; Berger 1990; Forman & Ennis 1992; Berger & Easterbrook 1993; Gemmell 1997, 1999), but in cases of associated sediments, a possible time-lag between till formation and its associated sediments has to be considered. The importance of a time-lag, again, is related to the sediment age, where a time-lag in the range of a few 1000 yr might be negligible for sediments of the early part of the last glacial cycle, but would not be for Lateglacial and Holocene age sediments.

(2) Glacially associated sediments that experience an additional reworking cycle, thus increasing the potential for daylight exposure, are favoured over till. The additional step of sediment reworking, however, does not necessarily guarantee sufficient bleaching and in the case of glaciofluvial, glaciolacustrine and glaciomarine sediments, daylight is greatly attenuated by the water column and increased turbidity (Berger 1990; Ditlefsen 1992; Fuchs *et al*. 2005). Glacioaeolian sediments, therefore, represent the best choice for dating because of the more prolonged exposure to daylight that is associated with aeolian transportation and sedimentation (see Derbyshire & Owen 1996; Bateman 2008) and consequently results in sufficient bleaching. Glaciofluvial sediments are particularly prone to bleaching problems, but fine-grain sediments (*c*. 4–11 μm) seem to be better bleached than coarse grains (*c*. 90–200 μm). This might be related to the slower deposition of fine grains out of the water column, thus longer exposure to daylight (Berger & Easterbrook 1993; Fuchs *et al.* 2005). Sampling distal to the turbulent fluvial channel, where sedimentation conditions are much calmer, might be more effective for signal resetting of the fine-grain fraction than proximal channel deposits and could provide more accurate luminescence ages. Owing to the slower deposition of the fine-grain fraction, finer-grained sediment is also favoured when sampling glaciomarine and glaciolacustrine sediments. The probability of signal resetting for glaciolacustrine sediments might be additionally enhanced by wave activity and the resulting sedimentary grains washing up and down the beach. Fine-grained sediment, however, has the tendency to coagulate; thus the inner grains of these grain aggregates are shielded from light reducing their potential to be bleached.

(3) Luminescence dating of quartz is favoured over feldspar because, as Godfrey-Smith *et al.* (1988) showed, the quartz luminescence signal bleaches faster than the feldspar signal (Fig. 8). This is also supported by the work of Fuchs *et al.* (2005) on modern fluvial sediments. In addition, quartz does not suffer from anomalous fading (Aitken 1985), a common problem of feldspar. Feldspar, however, does have the advantage

that it can be used to date sediments over a much larger time range than quartz.

(4) To test for internal chronostratigraphic consistency, multiple luminescence samples should be collected at each site/locality when possible. In particular, samples should be collected from different sediment types along the same stratigraphic horizon to help test for bleaching problems, and from positions stratigraphically higher and lower to test for stratigraphic coherence. Age reversals can be an indicator of age overestimation for some samples due to insufficient bleaching. Alternatively, this may represent an underestimate of age if, for example, there has been a significant dose rate increase in the sampled part of the section due to translocation of leaching or mineral at the site throughout its history.

(5) Glacigenic sediments are often characterized by a high content of gravel, which makes sediment sampling by hammering an opaque cylinder into the sediment difficult or even impossible. In these cases, sampling at night should be undertaken by directly sampling a freshened, but dark, exposure and immediately packing the samples into opaque light proof bags. It is important before sampling that the light-exposed sediment layer has been removed from the exposure and that during sampling the samples are not contaminated by sediment falling from the light-exposed sediments above the sampling site. Even when samples are easy to sample, for example, fine-grained sands, great care should be taken to ensure that none of the sediment is exposed to light while sampling and during transport to the laboratory. Samples should always be collected in opaque tubes and wrapped in light-proof bags.

(6) When sampling for dose-rate measurements, it is important to have a representative sediment sample of the sedimentological context from 30 cm around the sampling position of the main luminescence sample. To avoid sedimentological heterogeneity problems, the luminescence samples should be taken from the centre of a 60 cm thick and sedimentological homogeneous layer, which allows a more likely representative dose-rate sampling. Alternatively, *in situ* dose-rate measurements can be carried out by (a) portable gamma ($\gamma$-) spectrometer or (b) buried artificial dosimeters, such as $\alpha$-$Al_2O_3$:C pellets, which both account for sedimentological heterogeneity (Burbidge & Duller 2003). An accurate measurement and estimate of former water content is important in determining the dose rates, since the presence of water reduces the effective dose rate. A 1% difference in water content results in *c.* 1% difference in OSL age. Variation in water content in glacial and associated sediments can be considerable, as associated ice and meltwater bodies dewater or saturate the sediments. Understanding the palaeoenvironmental setting and history is therefore essential for good estimates of changes of water content throughout the sediment's history. Table 3 highlights the environments and sediments most likely to experience problems with dose-rate variability and possible radioactive disequilibrium (Krbetschek *et al.* 1994; Olley *et al.* 1996, 1997).

As highlighted above, sampling for luminescence dating requires mature consideration before and during sampling. For this reason, the field geoscientist and the luminescence dating scientist should come together on site to discuss the sampling strategy for luminescence dating. Furthermore, applying multiple dating

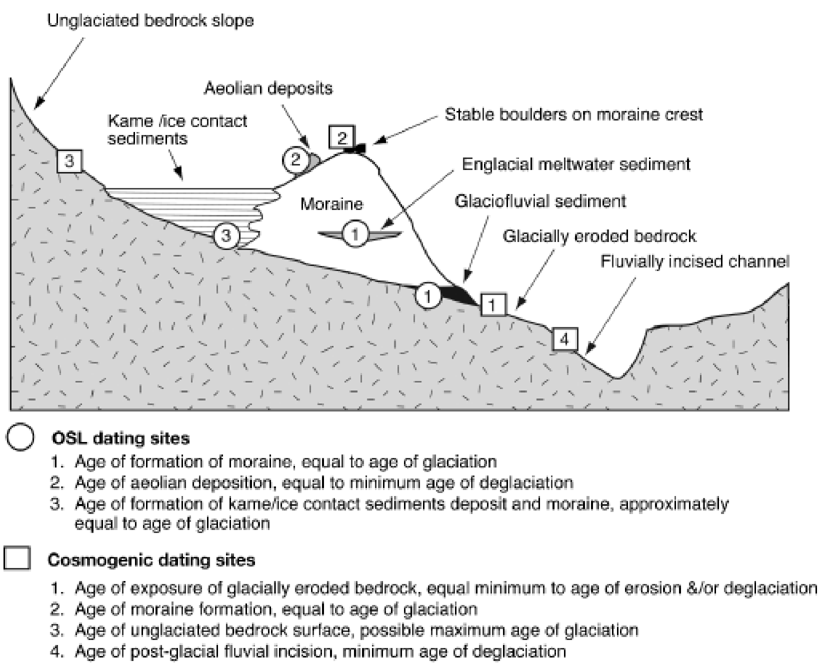


*Fig. 11.* Sampling strategies for OSL and CRN dating of moraines and associated deposits and landforms showing the significance of each dating site (adapted from Benn & Owen 2002).

techniques, such as TCN methods, provides an independent assessment of the luminescence ages. Benn & Owen (2002) discuss the strategies for combining TCN and luminescence dating to glacial sediments, emphasizing how they can be used to provide both minimum and maximum ages on glaciation (Fig. 11).

## Future directions

Recent advances in the dating of glacigenic sediments result from the development of single-aliquot and single-grain measurements using SAR (Murray & Wintle 2000; Duller 2004); these allow investigation of the sediment's bleaching characteristics and enable the calculation of reasonable $D_e$ estimates for an insufficiently bleached sample. In the case of single-grain measurements, the statistical $D_e$ analysis is generally based on the measurement of several thousand grains per sample, because only a small percentage of grains show reasonable luminescence characteristics for $D_e$ calculation (Duller 2006; Glasser *et al.* 2006). Single-grain data analysis is time consuming and a more automated analyse procedure would be a step forward in the application of single-grain measurements. A further challenge represents the interpretation of $D_e$ distributions from single-grain measurements, where a broad distribution is thought to be the result of heterogeneous bleaching of the individual grains. Variations in microdosimetry, however, can contribute to the broad $D_e$ distribution, especially where the mineralogical context of the sediment is heterogeneous, which is often true for till. Unfortunately, the individual dose rate for the single grains cannot be assessed, since each grain's context is destroyed using the current techniques for single-grain sample preparation. Using spatially resolved high-resolution OSL (HR-OSL), the mineralogical context of intact sediment or rock surfaces can be assessed (Habermann *et al.* 2000; Greilich & Wagner 2006) and dose-rate determinations can be spatially resolved to obtain the dose rate for every grain or given area (Wagner *et al.* 2005). In practice, this new technique was successfully applied to stone surfaces from Germany and Peru (Greilich & Wagner 2006), and shows great potential for glacigenic sediments, particularly for boulders on moraines.

Despite recent advances in single-grain and single-aliquot measurement techniques for $D_e$ determination, interpretation of the $D_e$ distribution for reasonable age estimations is challenging and several methods are suggested (see above; Galbraith & Laslett 1993; Olley *et al.* 1998; Fuchs & Lang 2001, Lepper & McKeever 2002). Using decision supported criteria, Bailey & Arnold (2006) suggest which model fits best for a certain $D_e$ distribution to extract reasonable $D_e$ estimates. Alternatively, linear modulation (LM) techniques can be applied to insufficiently bleached sediments (Bulur 1996; Bailey 2000; Singarayer *et al.* 2005), which has great potential for accurate $D_e$ determination for insufficiently bleached sediments. Presently, user-friendly software for the analyses of LM data that would support the broad application to glacigenic sediment hardly exists (Choi *et al.* 2006). The development of such software would greatly benefit the user community.

The preference for the use of quartz in luminescence dating is mainly due the problem of anomalous fading associated with feldspar. The advantage of feldspar is its much brighter luminescence signal and its higher saturation characteristics. The latter would enable feldspars to be used to obtain ages of $>150$ kyr. Procedures that correct for anomalous fading are in development, and these would result in a wider use of feldspar for dating purposes (Huntley & Lamothe 2001; Auclair *et al.* 2003; Lamothe *et al.* 2003).

In addition to the developments in $D_e$ determination, dose-rate estimations based on mass spectrometry measurements have become more common in recent years. The small sample quantities used for this laboratory-based analysis make it difficult to have representative samples in mineralogically heterogeneous sediment. Alternatively, on-site measurement techniques which account for sediment heterogeneity can be applied for dose-rate estimates. Hand-held $\gamma$-spectrometers are becoming more conveniently designed for on-site application and new NaI based $\gamma$-spectrometers compensate for temperature variations. Another on-site method for estimating the dose rate is based on the use of a synthetic and highly sensitive dosimeter like $\alpha$-$Al_2O_3$:C (Akselrod *et al.* 1990), which needs burial times of only several days to weeks (Burbidge & Duller 2003; Kalchgruber & Wagner 2006), instead of a one year burial time as for formerly used dosimeters like LiF.

In recent years, luminescence dating has made significant technical and methodological progress since the initial TL dating of glacigenic sediments. This has resulted in many successful dating projects to define the age of glacigenic sediments and timing of glaciation. Ongoing methodological and technical developments are promising, and hopefully will soon enable the dating of sediments that cannot presently be dated by luminescence methods. Nevertheless, luminescence dating of glacial and associated sediments is not routine, like radiocarbon dating, but still represents a challenge for the scientific luminescence dating community. Projects applying luminescence dating, therefore, should describe and document the procedures used for luminescence age calculation to be able to understand, assess and evaluate the reliability of any presented luminescence age.

There is much value in combining different dating techniques, such as TCN and U-Series dating with luminescence dating, to test the accuracy of each different dating method. The studies in the Hunza Valley and Khumbu Himal are a first step in this direction (Richards *et al.* 2000b; Finkel *et al.* 2003; Owen *et al.* 2002b; Spencer & Owen 2004). Furthermore, combining multiple dating methods promises to provide important insights into geomorphic, geochemical and geophysical processes.

## Conclusions

Recent developments in luminescence dating are providing opportunities for dating a broad range of late Quaternary glacial landforms and sediments. Notable studies include mountain glacial successions in the Himalaya and areas formerly within or marginal to the European ice sheets, such as in Scotland and Fennoscandia. OSL dating of quartz utilizing SAR methods is currently favoured for dating glacially associated sediments since the fast OSL component of quartz is rapidly bleached by sunlight; thus, problems associated with insufficient bleaching can be readily identified. Other problems of note include thermal transfer, low luminescence sensitivity of quartz, and variable dose rates during the history of the sediment due to changing water content or nuclide leaching. These problems can often be addressed by careful sampling and descriptions of the sampling site; these require an understanding of the nature of glacial and associated environments to select the most appropriate sediment samples for dating, testing for insufficient bleaching and modelling dose-rate variability. A summary of the sediment types and potential bleaching and dose-rate problems is provided in Table 3. Future developments include increased use of small single aliquots, single-grain dating and improved dose-rate determination such as the use of portable field $\gamma$-spectrometers.

*Acknowledgements*. – Many thanks to Ann Wintle, Alastair Gemmell and an anonymous reviewer for their constructive and informative reviews of our article. We also thank Glenn Berger for advice on Tables 1 and 2. Thanks to Tim Phillips for drafting Figures 1 to 6 and 11, and to Jason Dortch for allowing us to use data from his Master's thesis to help construct Figure 9.

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