

Luminescence dating of sediments using individual mineral grains

GEOFFREY A. T. DULLER¹ & ANDREW S. MURRAY²

¹ Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, UK

² Nordic Laboratory for Luminescence Dating, Department of Earth Sciences, University of Aarhus, Risø National Laboratory, DK-4000 Roskilde, Denmark

Abstract: Luminescence is widely used to produce absolute ages for the time of deposition of a variety of types of sediments. The method relies upon the assumption that all grains are exposed to sufficient daylight prior to deposition for their luminescence signal to be reduced to a negligible level. Recent research has focused on the analysis of the luminescence signal from single mineral grains to produce an age. At this scale it is possible to identify different populations of mineral grains within a sample – some of which were bleached at deposition and some which were not. The methods involved in such analyses are discussed, and examples are given of depositional environments where this type of analysis is essential.

Key words: luminescence dating, laboratory technique, measurement protocols, single grains, OSL.

Introduction

Luminescence dating is now an important tool for obtaining absolute age estimates for sedimentary deposits. Recent reviews (e.g. Duller 1996; Aitken 1998) have highlighted the increasing use of optically stimulated luminescence (OSL) measurements instead of thermoluminescence (TL). OSL is much better suited to dating geological materials since the same process of optical resetting of the luminescence signal is used in the laboratory and in nature, and less exposure to daylight is required to reset the OSL signal than TL. However, another major advance in the last ten years has been the adoption of new measurement procedures that have permitted analysis of samples using smaller amounts of material.

Luminescence dating is based on the measurement of two quantities, the radiation dose received by a sample since burial (the palaeodose, P) and the rate at which it has absorbed energy from the natural environment (the dose rate). Of these, it is the palaeodose that is derived from luminescence measurements. Dividing one quantity by the other gives the period of time since deposition of the sediment:

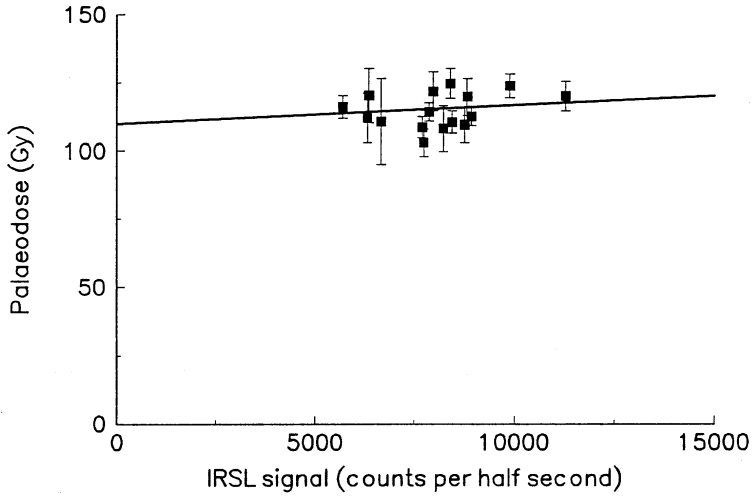
$$\text{Age(years)} = \frac{\text{Palaeodose(Gy)}}{\text{DoseRate(Gy/year)}}.$$

An essential assumption of the method is that the luminescence signal from a grain can be reset, or zeroed, by exposure to daylight. This is a process commonly termed 'bleaching' and occurs in many processes of erosion, transportation or deposition, particularly those that occur sub-aerially. Prior to 1991, almost all palaeodose measurements were made using many tens of thousands of grains of a sample, spread between many tens of sub-samples, or aliquots. An implicit assumption within all of these methods, known as multiple aliquot methods, was that the luminescence characteristics of each aliquot were identical. This required either a completely homogeneous sample, or the use of aliquots of a sufficient size to average out any variations. Where there were significant differences between the grains, possibly due to differing extents of bleaching at deposition, this was seen as scatter in the data and resulted in uncertainty in the final age estimate produced (Huntley & Berger 1985). More seriously, the presence of a few very bright grains which had not been bleached at deposition could lead to a significant overestimate of the age. For instance, Duller *et al.* (1995) showed that a glacio-fluvial deposit from Scotland yielded an OSL age that was at least five times older than independent age estimates. Within the last 10 years methods have been developed that can measure the palaeodose from single aliquots and, more recently, single sand-sized mineral grains. This has important implications for the potential of luminescence dating and its reliability. This paper outlines the procedures involved in such measurements, and their advantages.

Single aliquot methods

A number of luminescence workers have suggested that it would be feasible to make all the measurements necessary to calculate a palaeodose on a single aliquot. Duller (1991, 1994a) was the first to demonstrate how this could be undertaken in practice, and these methods have been used widely. This was an important development for a number of reasons. Firstly, for dating geological sediments it meant that if a sample contains a mixture of grains, some of which had been bleached at deposition and some of which had not, this could be identified. In such a situation, different aliquots would contain different proportions of well bleached and unbleached grains and hence give different palaeodo-

(a) Bythe Lower Gravel



(b) Bythe Windermere Interstadial

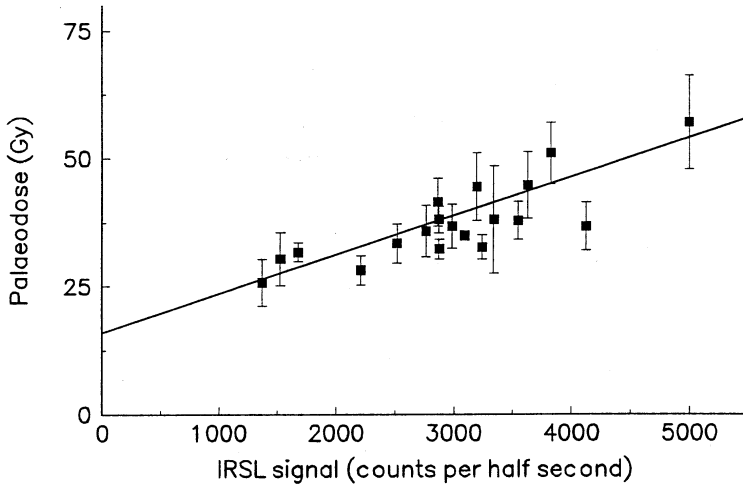


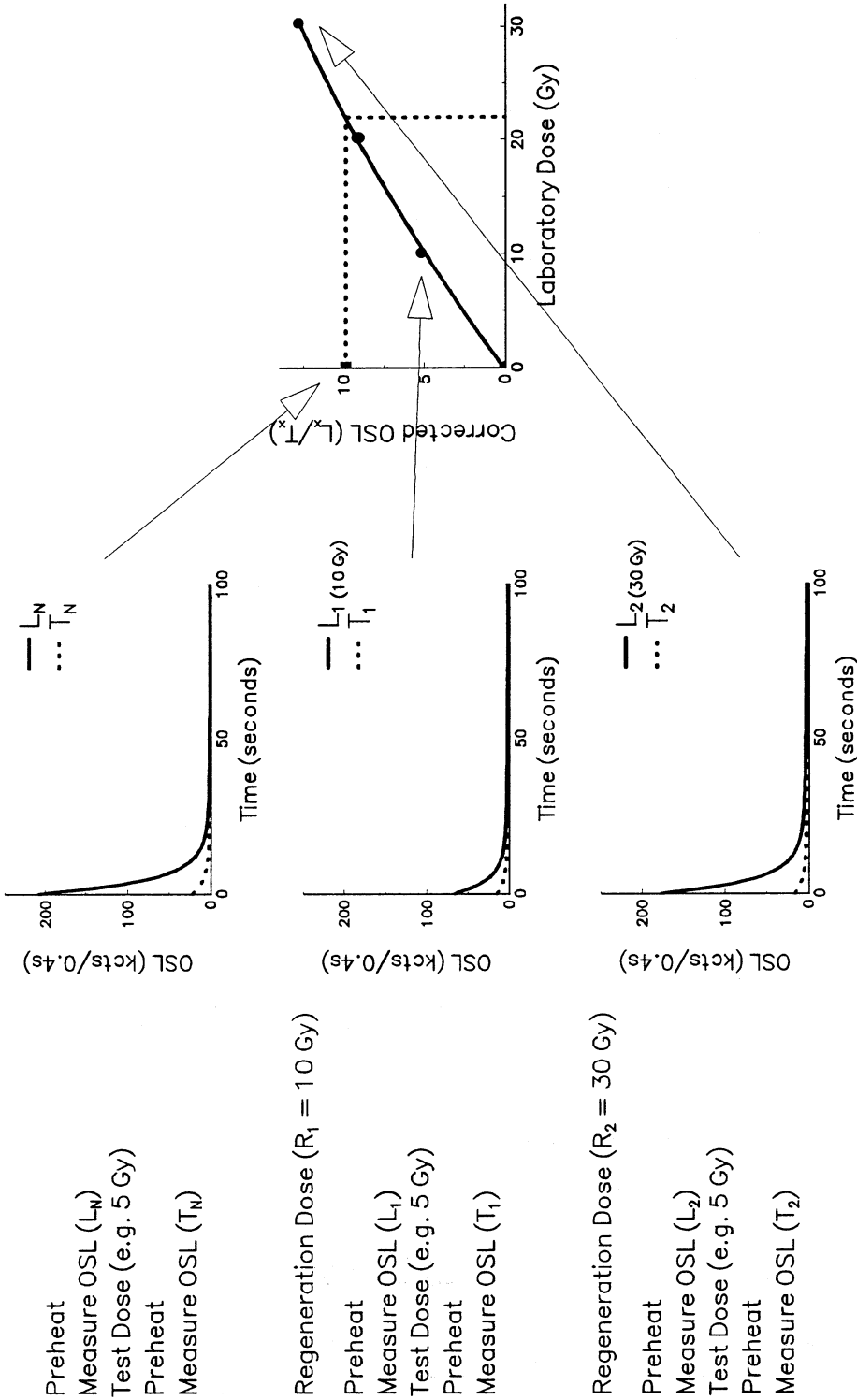
Fig. 1. Palaeodose plotted against the intensity of the natural signal for a set of aliquots from (a) a well bleached sample (Bythe Lower Gravel – BLG) and (b) a poorly bleached sample (Bythe Windermere Interstadial – BWI). In each case the data were obtained using an additive dose single aliquot procedure applied to potassium rich feldspars separated from late Quaternary fluvioglacial sands from Scotland. Further details of the two sites are given in Duller (1994b).

ses (e.g. Li 1994). Only those grains whose luminescence signal was fully reset at deposition would give an accurate palaeodose, and hence age; if a sample contained some fraction of unbleached grains the palaeodose would be overestimated, and so would the age. A number of different approaches have been developed to analyse such data, both to identify those samples where this is a problem, and in an attempt to provide an upper limit on the age estimate (e.g. Li 1994). The most important method has been to produce a scatter plot of the values of the palaeodose and the OSL signal intensity from a number of aliquots of the same sample. If a sample contains only well bleached grains then the palaeodose derived from each aliquot will be similar, and there should be little variation in signal intensity (Fig. 1a). In contrast, where a mixture of bleached and unbleached grains are present, a wider range of palaeodoses will be observed, and those aliquots with the larger palaeodose will also tend to have a brighter luminescence signal (Fig. 1b). A linear regression line is placed through the data, and if the slope of the line is significantly greater than zero then it is deduced that the sample is incompletely bleached. This approach has been applied to fluvial, colluvial (Wintle *et al.* 1993) and glacial (Duller 1994b) sediments, but is equally applicable in other depositional environments where the degree of optical bleaching at deposition is uncertain (e.g. coastal storm and tsunami deposits, mass movements, soil forming processes). This form of analysis relies upon an implicit assumption that within a sample all aliquots have a similar sensitivity to radiation, and produce a fixed OSL signal per unit dose. This assumption is reasonably valid for potassium-rich feldspars when analysing many grains on an aliquot, and all the examples listed above conform to this condition. However, for other materials such as quartz, or when the number of grains in a sub-sample is small, this assumption is not valid and different methods of analysis are required.

Results from small numbers of grains

Initial single aliquot work concentrated solely on the use of potassium-rich feldspars as the dosimeter. However, Murray *et al.* (1995, 1997) and Murray (1996) developed single aliquot analysis procedures that could be used with quartz, a more ubiquitous mineral component of detrital sediments. Although the methods involved are different, the advantages of such measurements are the same.

The most robust of the methods developed for quartz is known as the single aliquot regenerative (SAR) dose procedure and has been described recently in Murray & Wintle (2000). A brief summary is given here since many of the results described in this paper have been obtained with this method. In essence the procedure is very simple. In order to measure the palaeodose from a sample, the natural OSL signal from an aliquot is measured. This measurement empties



Preheat
 Measure OSL (L_N)
 Test Dose (e.g. 5 Gy)
 Preheat
 Measure OSL (T_N)

Regeneration Dose ($R_1 = 10$ Gy)

Preheat
 Measure OSL (L_1)
 Test Dose (e.g. 5 Gy)
 Preheat
 Measure OSL (T_1)

Regeneration Dose ($R_2 = 30$ Gy)

Preheat
 Measure OSL (L_2)
 Test Dose (e.g. 5 Gy)
 Preheat
 Measure OSL (T_2)

Fig. 2. The Single Aliquot Regenerative dose method (SAR). A series of OSL measurements are made of the natural signal (L_N), and the response to various regeneration doses (L_1, L_2 etc.). After each measurement, the sensitivity of the sample is measured by giving a standard radiation dose (the 'test dose') and measuring the OSL signal produced (T_N, T_1, T_2 etc.). The response of the sample to dose can be plotted on a graph of the ratio of L_x/T_x as a function of laboratory dose. The palaeodose of the sample is calculated by interpolating the value of L_N/T_N onto this response curve. For this sample, the palaeodose is 22 Gy.

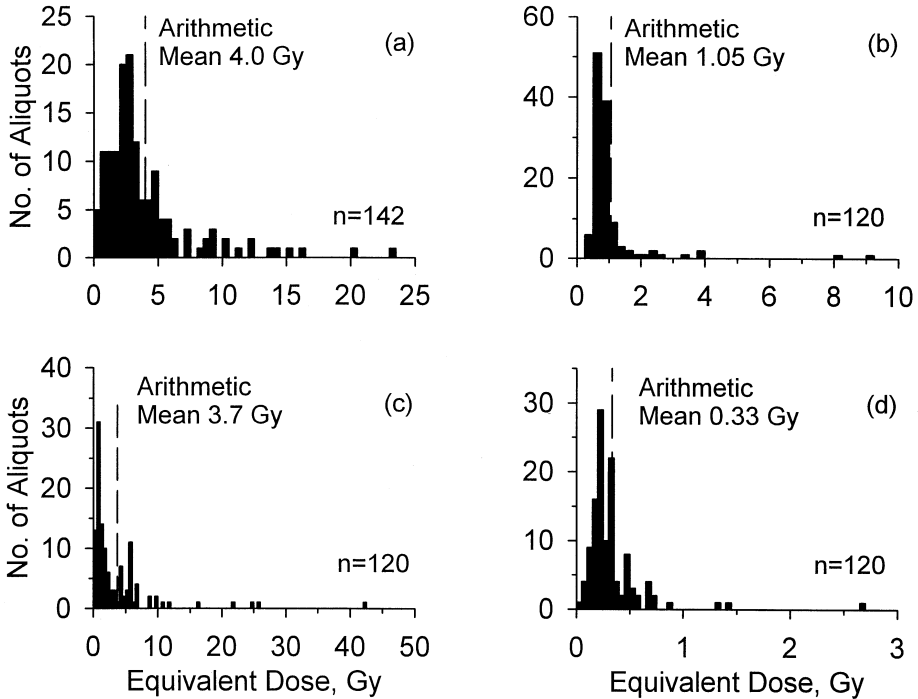


Fig. 3. The distribution of apparent dose in young fluvial sediments from south eastern Australia. Measurements were made on single aliquots of quartz (from Murray *et al.* 1995). The samples were (a) a sub-aqueous fan in a small farm dam, (b) an inchannel flood deposit, (c) a bed channel deposit and (d) an overbank deposit.

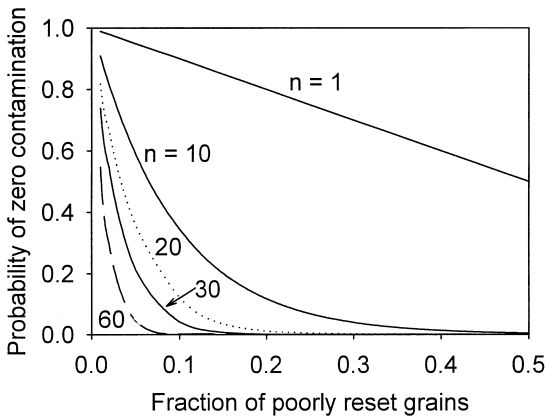


Fig. 4. In a mixture of bleached and unbleached grains, the probability of selecting only well-bleached grains decreases as the number of grains on an aliquot (n) increases, and as the fraction of the grains which are unbleached increases (from Olley *et al.* 1999). For many samples the proportion of grains that contribute significantly to the total luminescence signal is small, and hence the effective value of n may be much smaller than the actual value (see Fig. 8).

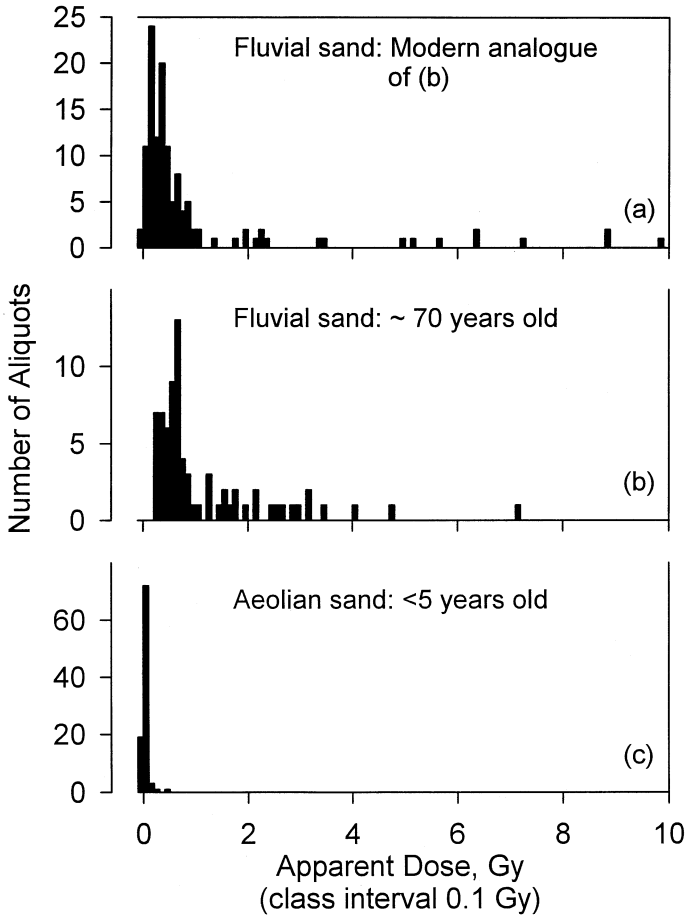


Fig. 5. The palaeodose obtained from measurements of many small aliquots, with between 60 and 100 grains on each, from a range of samples from south-eastern Australia (from Olley *et al.* 1998). For fluvial samples where the degree of bleaching at deposition is lower, the range of palaeodoses is wider than that from the aeolian sample.

the majority of the OSL from the sample. A laboratory dose can then be administered to the sample and the OSL signal (regenerated by that dose) measured. This can be repeated a number of times with different regeneration doses in order to characterise the way that the OSL signal grows with radiation dose. From this response, the laboratory dose required to match the OSL signal obtained from the natural measurement can be calculated (Fig. 2). This is called the equivalent dose (D_E) or the palaeodose (P).

In practice, there are additional complications. The first is that it is necessary to apply heat to the sample prior to each OSL measurement so that all the measurements are comparable. This preheat, along with the OSL measurement itself, alters the response of the sample, known as its sensitivity. These changes

in sensitivity prevented previous workers from using such an elegant and simple solution (e.g. Duller 1991; Stokes 1994). Murray & Wintle (2000) overcame sensitivity changes by developing a method which explicitly monitors the sensitivity during a set of measurements (Fig. 2). After measurement of the OSL signal relating to the natural dose or one of the laboratory regeneration doses (L_x), an extra set of measurements are inserted. The aliquot is given a small radiation dose, called the test dose, heated to 160°C to remove any signals that would interfere with the main OSL measurement, and its OSL signal measured (T_x). The same test dose is used throughout a set of measurements on an aliquot. If no sensitivity changes occurred then all values of T_x would be identical. In practice this is not seen, and instead of plotting the raw OSL signal (L_x) to construct a growth curve, the results are normalised by the response to the test dose (L_x/T_x) to correct for sensitivity change.

Work by Murray *et al.* (1995) using an early version of the SAR procedure, and small aliquots of only a few hundred grains, showed how modern samples collected from a variety of fluvial depositional environments contained differing proportions of unbleached, or incompletely bleached, grains (Fig. 3), with an overbank deposit being the most well bleached. In this case the distribution of palaeodoses observed from these grains are presented as histograms since it is known that different quartz grains have very different sensitivities to dose.

Where a mixture of grains is present, the probability of obtaining a sub-sample containing only well bleached grains decreases rapidly as the number of grains in the sub-sample increases (Fig. 4, from Olley *et al.* 1999). Thus in his early work Li (1994) reduced the number of grains present in his aliquots in order to accentuate the differences in palaeodose and this approach has also been used successfully by Olley *et al.* (1998). Figure 5 shows the distribution of palaeodose values in aliquots of quartz which contain between 60 and 100 grains (as opposed to approximately 5000–10000 grains, which is more typical of traditional measurements). These results show the difference in the luminescence signal from young sediments in fluvial and aeolian depositional environments. A significant number of the aliquots from the fluvial sediment contain grains whose luminescence signal was not reset at deposition and so give palaeodoses that are much larger than would be expected for a sample that was less than 5 years old.

Olley *et al.* (1998) suggested that a distribution of palaeodose values would be observed where a proportion of the grains within a deposit were not fully reset at deposition. In this situation, they showed that the best estimate for the palaeodose that has accrued since the last bleaching event was obtained by taking the average value from the 5% of the aliquots with the lowest palaeodose. This was tested by applying the method to samples extracted from a sediment core from the Namoi river. The results were encouraging, though there was no definite age control.

Lepper *et al.* (in press) also obtained palaeodose distributions for samples from different depositional environments using quartz single aliquot measure-

ments. They used a deconvolution method to remove any measurement uncertainties and then calculated the palaeodose relating to the latest depositional event by taking the mean of the value between the lowest palaeodose measurement and the peak of the distribution. Although this data gave stratigraphically consistent results, there was no good age control with which to compare the results.

Results from individual grains

The methods used by Olley *et al.* (1998) and Lepper *et al.* (in press) both attempt to separate from a mixed population of mineral grains the palaeodose of those grains which have been bleached during the most recent depositional event, and so remove the effect of those grains which were not bleached. A more direct method of achieving this same objective is to make measurements of the palaeodose from individual grains.

Lamothe *et al.* (1994) presented palaeodoses for 15 grains of potassium feldspar extracted from a shallow marine late-glacial sediment in Quebec. In the case of potassium rich feldspars a significant proportion of the total dose to the sample originates from the decay of ^{40}K within the grain. Particularly large grains (750–1000 μm diameter) were used in this study in order to facilitate manipulation of the grains by hand during luminescence measurement. As a consequence, at least 50% of the total dose rate arose from within the grains. The ages calculated for the 15 grains varied from 700%, to approximately 70% of the estimated age. The presence of grains with significant age overestimates demonstrated the benefit of single grain analysis for inadequately bleached samples. It was more difficult to explain the presence of grains which underestimated the expected age, but this may have been caused by a phenomenon termed 'anomalous fading' which can affect measurements of feldspars (e.g. Spooner 1994).

Murray & Roberts (1997) were the first to obtain palaeodoses from individual sand-sized grains of quartz. In their samples from Australia they noted that within a single sample they observed a broad range of OSL signal intensities, varying by several orders of magnitude. The range of palaeodose values from a single sample was also broad, but for these sub-aerial samples the values were consistent with a single age for the sediment.

More recently, the benefit of single grain analysis has been demonstrated very clearly by the work of Roberts *et al.* (1999) at a site called Jinmium, in north-west Australia. Jinmium is an important Aboriginal rock shelter site, with archaeological evidence of human activity. The site was first brought to prominence by Fullager *et al.* (1996) where thermoluminescence dates (using large aliquots of ~10 000 grains) measured on sands collected from an excavation at the base of the rock shelter suggested that humans had arrived at this site prior to 116 ± 12 ka, almost 50 kyr earlier than previous estimates for the first human arrival in the continent (Roberts *et al.* 1994). However, the site at Jinmium is

a complex one for luminescence dating. The 'rock shelter' consists of a slightly overhanging sandstone rock face. Blocks of sandstone that had fallen from the overhanging face were encountered during the excavations at the base, mixed together with sand that was thought to have blown into the site from the surrounding area. If the blocks disintegrated *in situ* then the grains released would not be exposed to daylight. The presence of such grains mixed with those that were delivered by aeolian processes would lead to an overestimate of the age. Single grain analysis suggested that this had occurred (Roberts *et al.* 1998) and that if only those grains from the younger population were included in the analysis then a depositional age of younger than 10 ka was more appropriate.

In the last year, single grain analysis has also been used for dating fluvial sediments. Exposure of mineral grains to sunlight during transport may occur on a discrete basis, but in certain fluvial settings some grains may remain unbleached. As with Jinmium, the application of standard multiple grain analyses will result in an age overestimate. Olley *et al.* (1999) have shown that such heterogeneous bleaching does occur in some fluvial deposits, and that single grain analysis provides a means to obtain accurate depositional ages.

Practical difficulties

Analysis of single mineral grains 100–300 μm in diameter is complex. The luminescence signal from single grains tends to be weak, and manipulating such grains in laboratory conditions is difficult (all samples have to be handled under dim red light prior to analysis in order to prevent loss of the light-sensitive luminescence signal). Three methods have previously been developed to cope with the analysis of single grains. The first, and most widely used, is to hand-pick individual grains and mount them on standard aluminium sample holders. These holders are 9.7 mm in diameter and are designed to accommodate many thousand grains. However Lamothe *et al.* (1994) and Murray & Roberts (1997) have successfully used this procedure for single grains. The advantage is that conventional luminescence equipment can be used for the measurements. However, the drawbacks are that it is laborious and that it makes very heavy use of instrument time.

A second approach has been to use an imaging system, such as an imaging photon detector (e. g. McFee 1998a) or a charge coupled device camera (e.g. Duller *et al.* 1997). Using such systems it is possible to mount many grains onto a single aluminium sample holder and then produce a two dimensional 'image' of the luminescence signal. Thus one can resolve the luminescence signal coming from individual grains. This has the advantage over hand picking grains that many grains can be analysed simultaneously. However these measurement systems are technically complex and expensive. Additionally, a critical issue is how reliably repeated measurements can be made on a single grain. This is

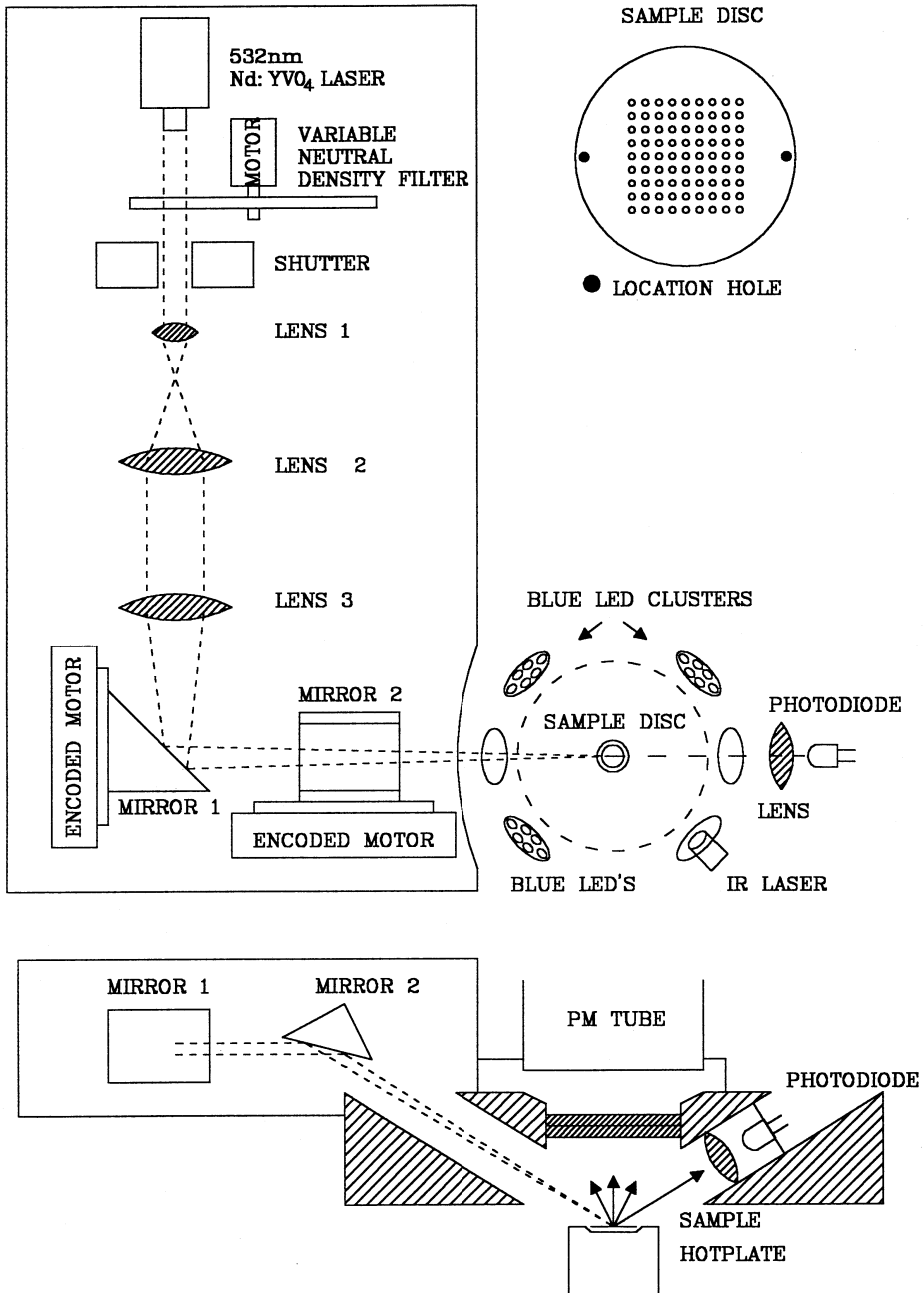


Fig. 6. Diagram of the optical stimulation section of the single grain luminescence system constructed at Risø. The path of the laser beam is shown by the dotted lines. It is focussed using a series of three lenses, and its precise position on the sample is controlled by moving the two mirrors. Single mineral grains are held in a nine-by-nine array of holes drilled into the surface of an aluminium disc. Further details of how the system works are given in Duller *et al.* (1999a, b).

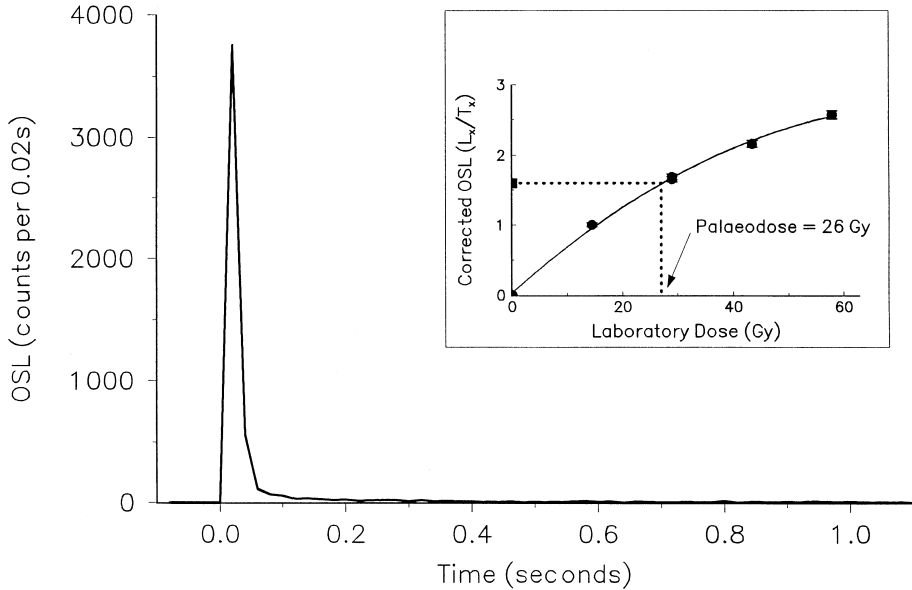


Fig. 7. An optically stimulated luminescence decay curve from a single grain of quartz extracted from a Tasmanian dune sand (TNE9503). A series of additional OSL decay curves were measured from the same grain after various treatments, following the procedure outlined in Fig. 2. The data were used to calculate a single aliquot regeneration (SAR) growth curve. This is shown as an inset to the main diagram. The corrected natural OSL signal (L_x/T_x) is shown as a solid square, while the regenerated signals used to define the growth curve are shown as solid circles.

essential for measurement of the palaeodose from a grain, yet McFee (1998b) calculated that the system based around an IPD had a 25% measurement uncertainty. However, in spite of these problems, such systems have been employed to measure palaeodoses (McFee 1998a).

A third approach, described by Bailiff *et al.* (1996), involved moving a standard aluminium sample holder under a focused laser beam so that each point on the sample was illuminated by the laser spot in turn, and the resulting OSL signal measured. While promising initial results were presented, the measurement time was prohibitive; the total scanning time for a single sample holder was at least one hour, and many such scans are required to derive palaeodoses from a single holder.

New technology

In the last two years a new piece of equipment specifically designed to make single grain luminescence measurements has been designed and built (Duller *et al.* 1999a, b). The system has two key features. The first is that the

standard 9.7 mm aluminium sample holder has been modified so that it contains an array of 81 holes drilled into its surface (Fig. 6). Each hole is 300 μm wide and 300 μm deep. Each hole centre is accurately drilled so that the grains lie 600 μm apart. The second key feature is a shuttered laser beam (532 nm, 10 mW) that is focused to a 20 μm diameter spot at the sample holder. This beam enters the measurement chamber via two mirrors which can be moved under computer control, and so allow the beam to be steered to any position on the sample holder. Thus the system can direct the beam at any one of the eighty-one grains mounted on the sample holder and stimulate OSL from that grain. This signal is then detected using a standard photomultiplier tube. The new single grain system has been designed to attach to an existing automated Risø TL/OSL reader so that it can benefit from having an automated sample changer, a heater stage that allows thermal pretreatment of the sample, and a beta source for irradiation. The total system can perform all the measurements necessary for palaeodose calculations under computer control without the need for an operator. Since the automatic sample changer can cope with up to 48 samples, and each sample holder can accommodate 81 grains, the system has a maximum capacity of just under 4000 grains, with a typical OSL measurement time of only about 200 s per disc.

Figure 7 shows an OSL decay curve measured using this automated system. This is the OSL signal from a single 180–211 μm diameter grain of quartz. The inset to the figure shows how the data from several such OSL measurements on the same grain can be used to construct a growth curve and hence to calculate the palaeodose.

Examples of single grain analysis

Grain brightness

Utilising the new equipment described above, it is possible to make luminescence measurements of many tens or hundreds of single grains. Duller *et al.* (in press) have used this instrument to measure the OSL signal from many grains within a sample. The general feature of all of these measurements is that there is a very large variability in the intensity of the luminescence signal obtained from different grains of the same sample. Previous authors have presented similar data as histograms of grain brightness (e.g. McFee & Tite 1998), but this is now considered inadequate because of the large dynamic range observed. An alternative way to present the data is as a cumulative sum, ranking the grains in order of descending brightness, and then plotting the cumulative light sum as a function of the proportion of the brightest grains involved (Fig. 8). If all grains gave the same OSL signal then a diagonal line would be plotted from the origin to the upper right hand corner of the diagram. In practice all samples will fall

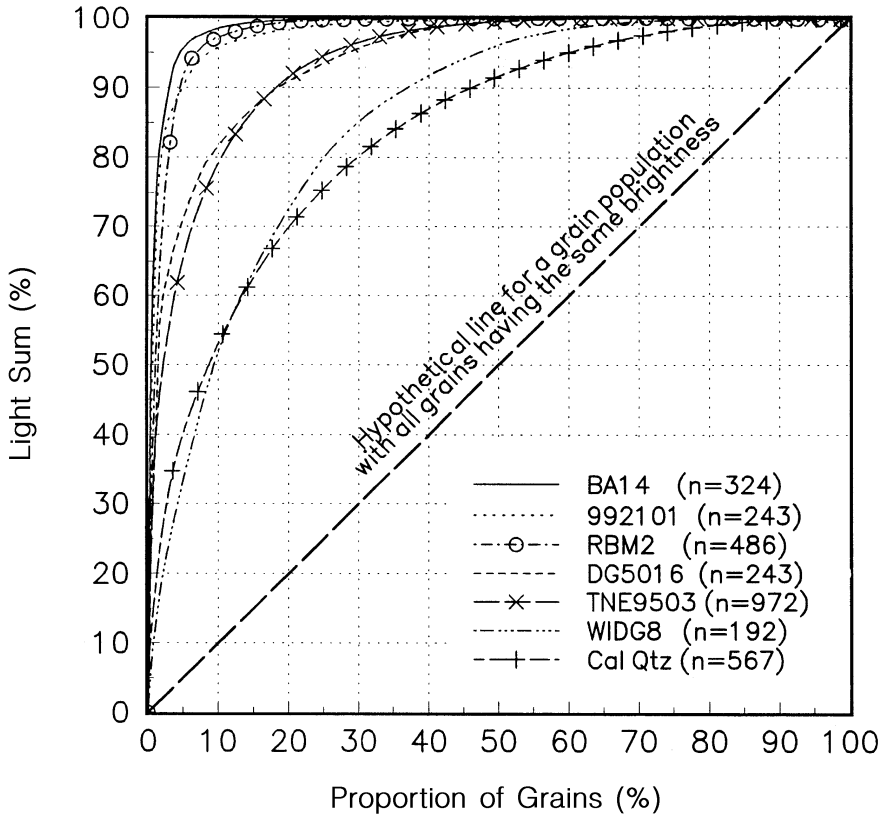


Fig. 8. The proportion of the total OSL light sum from a set of grains plotted as a function of the proportion of the brightest grains that are used. For a population of grains which all have the same brightness, the line would run diagonally from bottom left to top right. For all natural samples the line plots to the left of this. Data from a range of samples are shown. The number of grains measured from each sample is shown in brackets. Details of the samples are given in Duller *et al.* (in press).

above and to the left of the line. The further that a sample plots away from the 'ideal' diagonal line, the less even the distribution of signal within the different grains making up the sample. For instance, in samples BA14 and RBM2 (coastal aeolian sands from southern Africa), over 95% of the OSL signal originates from less than 5% of the grains, and the majority of the grains play a minor role in the overall signal. In contrast, WIDG8 (an aeolian sand from northern Australia) contains many grains that contribute.

Figure 4 showed that where a mixture of well-bleached and unbleached grains existed, the probability of selecting only well-bleached grains decreased rapidly as the number of grains increased. For multiple grain work this will give scatter in the palaeodose values obtained. If one compared the multiple grain

behaviour of two samples, such as BA14 with a few very bright grains and many dimmer ones, and WIDG8 with many similarly bright grains, they would be very different since the effective number of grains on an aliquot of equal mass is very different. This is an additional reason why single grain analysis is preferable to multiple grain analysis where there is a mixture of well-bleached and unbleached grains.

Palaeodose distributions

Figure 9 shows a set of palaeodoses obtained from 408 grains of a dune sand from north-east Tasmania. The sample dates from the last glacial maximum, and has not undergone any post-depositional reworking. An important consideration when analysing single grain data is how to present the results. As shown above, grains of quartz from a single sample may have OSL signals which vary by over two orders of magnitude. As well as affecting the multiple grain behaviour, this will influence the precision with which the palaeodose can be calculated. For the brighter grains the uncertainty may be 5%, while for dimmer grains it might be 100%. For such data it is unreasonable to present it as a histogram since this implicitly assumes that each data point should be weighted equally. Two alternative methods of presentation are possible. The first is to produce a probability density function (PDF). This is a weighted histogram where each palaeodose is represented by a gaussian curve whose peak is at the palaeodose value, but whose height is inversely related to the precision with which the palaeodose is known. Hence the result from a grain whose palaeodose is well known is represented by a narrow, high peak, while a grain whose palaeodose is poorly known is represented by a low broad peak. The results for all grains are then summed to produce a single probability density function (Fig. 9a). This approach has been criticised because it makes it impossible to discern the influence of an individual data point upon the overall distribution. Instead, Galbraith (1990) suggested using a radial plot (Fig. 9b). On this graph, each data point is represented discretely. Full details of how such plots are constructed are given by Galbraith (1990). The essential points are that the greater the precision with which a palaeodose is known, the further it is plotted to the right of the graph. The difference between some average palaeodose value and the value for the specific grain, divided by the standard error on that specific palaeodose dictates the vertical position of the point on the graph. A consequence of the quantities that are plotted is that any points lying on a line drawn through the zero point on the y-axis all have the same palaeodose. Thus a radial scale can be added on the right hand side of the graph, marked with values of palaeodose.

An additional advantage of the radial plot is that one can draw two parallel lines from the values $+2\sigma$ and -2σ on the y-axis to intersect the radial axis on the right hand side. Any data point whose palaeodose is consistent, within two

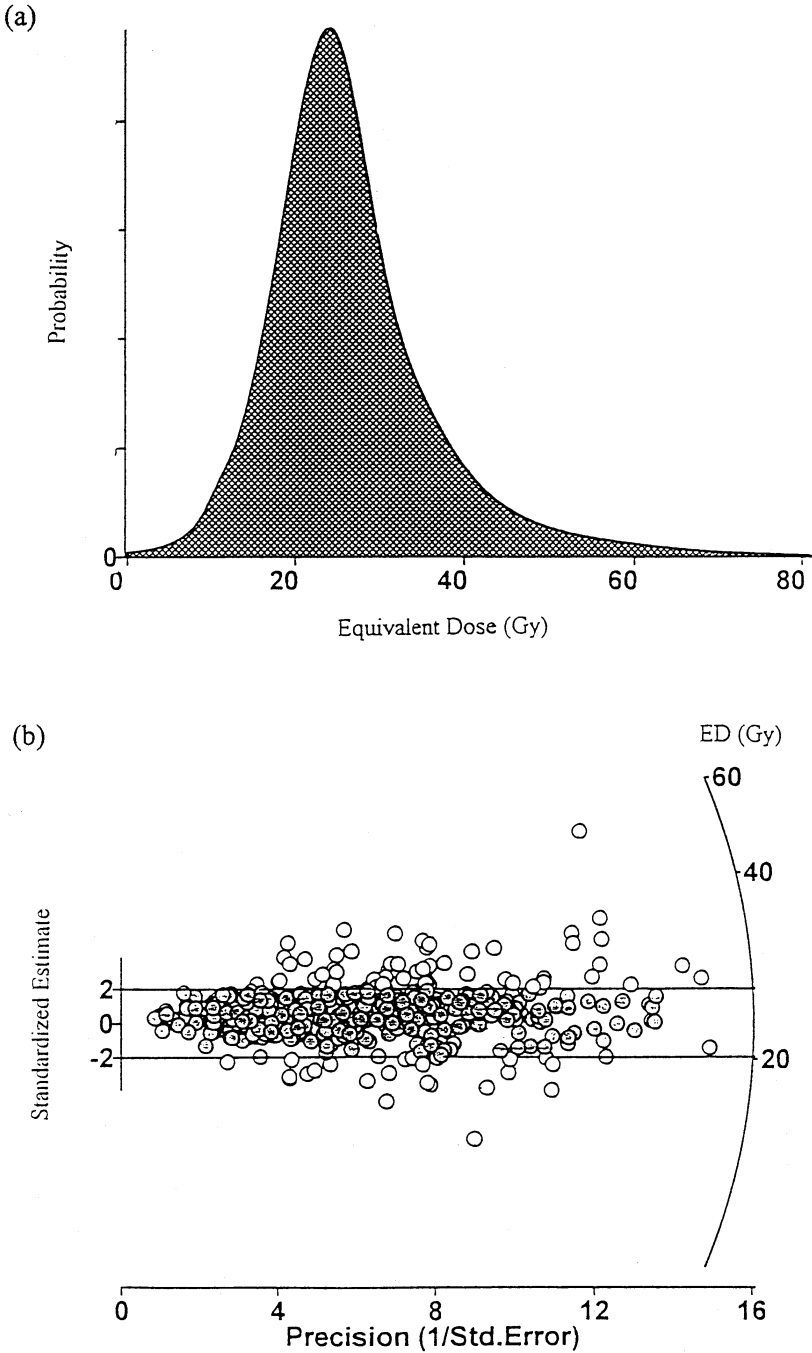


Fig. 9. Palaeodose measurements from 408 grains of quartz extracted from a Tasmanian dune sand (TNE9503). The palaeodose values are plotted (a) as a probability density function and (b) as a radial plot. The way in which such plots are constructed is described in the main text.

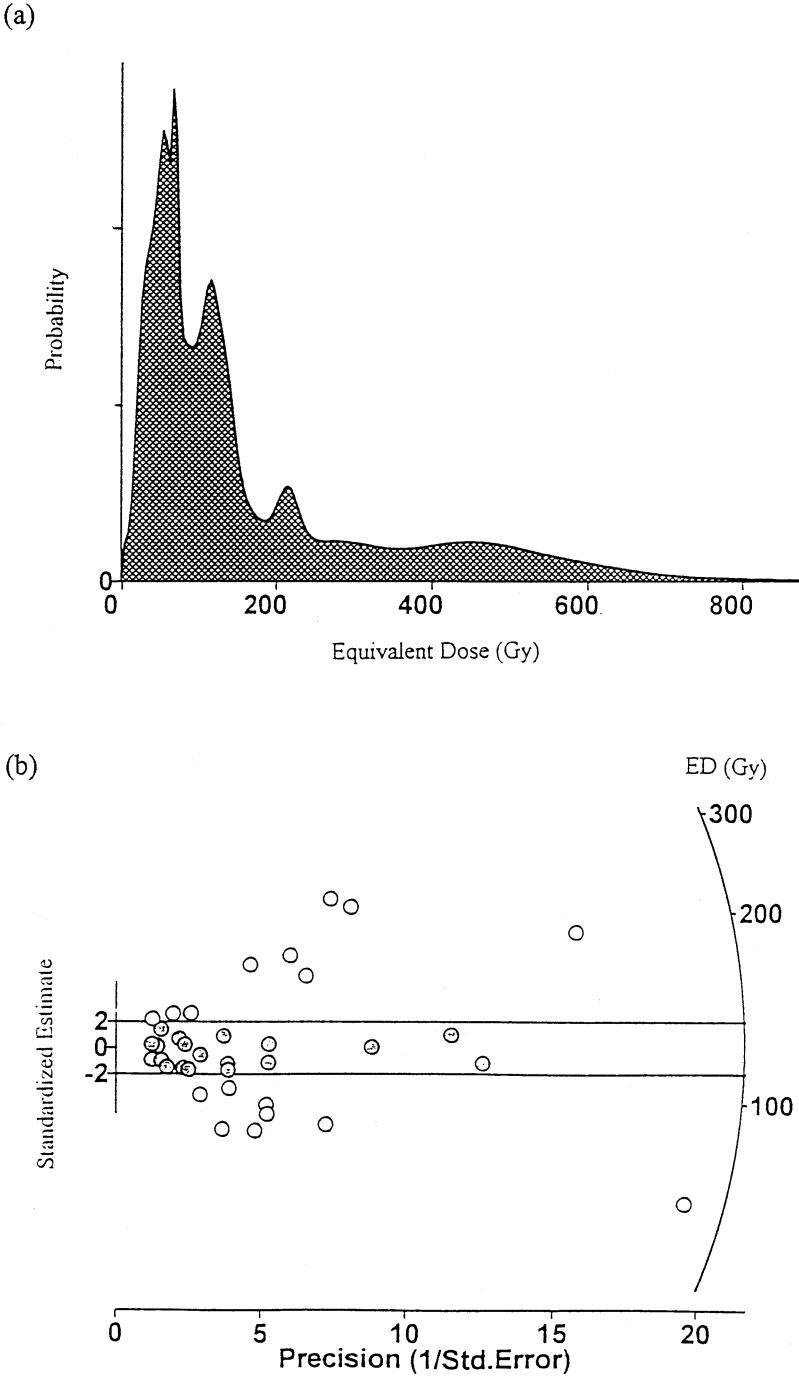


Fig. 10. Palaeodose measurements from 37 grains of quartz extracted from a frost-wedge cast, Denmark (992101). The palaeodose values are plotted as (a) a probability density function and (b) a radial plot.

standard deviations, with the mean palaeodose value used to construct the radial plot will fall within the band defined by these two lines. In the case of the aeolian sand from Tasmania, 81% of the grains do indeed fall within this band, demonstrating that the grains from the sample do yield a set of palaeodose values which are consistent with a single value of 22.8 ± 0.4 Gy, implying that the sample was well bleached at deposition.

In contrast, analysis of single grains from a sand infilling a frost-wedge cast (sample 992101) give a wide range of palaeodose values, and the radial plot (Fig. 10b) shows that only 51% of these are consistent with the mean value within two standard deviations. This sample clearly consists of at least two populations with a peak in the probability density function at approximately 50 Gy (Fig. 10a).

Conclusions

Luminescence dating methods have been applied successfully to sediments from a wide range of Quaternary sites over the last two decades. The development of single aliquot procedures for palaeodose determination has increased the throughput of samples, and reduced the analytical uncertainties.

The most successful depositional environments for luminescence dating are, not suprisingly, those in which the probability of grains being exposed to daylight at deposition is large, such as coastal and desert dunes (Wintle 1993) and loess. In such environments it is reasonable to assume that all grains have been equally bleached. However, there are a wide range of environments in which it is possible that grains have been adequately exposed to daylight, but it would be unwise to assume this to be the case. Sediments deposited by fluvial, glacio-fluvial and mass movement processes are likely to consist of a complex mixture of grains, with only a proportion having been completely exposed. In such situations the luminescence age calculated using standard multiple grain procedures will be an overestimate. A variety of methods have been developed which will identify such complex situations from single aliquot data, but which are unable to provide an indication of the extent of the overestimate. In such situations aliquots with a restricted number of grains may provide an estimate of the true palaeodose. A more direct method is to analyse single grains in order to directly differentiate between those grains which have been bleached and those which have not.

The development of single aliquot and single grain analytical procedures provide a new avenue of research in luminescence dating. The ability to analyse the luminescence properties of individual mineral grains within a sample widens the range of depositional environments in which the method can be applied, and provides far greater information about the sample than was available previously. Routine analysis of single grains is also being made practical by the development of instrumentation specifically designed for this purpose.

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