Estimation of equivalent dose in thermoluminescence dating - the *Australian slide* method

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Introduction
An inherent difficulty in estimating equivalent doses for TL and ESR dating is that the shape of the dose growth curve can be directly measured only for doses greater than the natural dose, N. This can be done by adding doses to natural samples to give a series of (N+dose) points. What is required from the sample, however, is the amount of dose received since the TL clock was reset either by heat or by exposure to sunlight. This means finding the point where the dose curve would have been, had it been measured at the time it began to grow after resetting. This requires assumptions about the shape of the "missing" part of the glow curve at doses less than N.

Various approaches to this problem were discussed in the review paper of Wintle and Huntley (1982) and are summarised in Aitken (1985) and by Berger (1988). In one form or other they involve an extrapolation, which is direct in the case of the additive (including partial bleach) method, or implied in the regeneration method. In the first case it is assumed that the model used to fit the (N+dose) data correctly models the behaviour of the dose curve when extrapolated. In the case of regeneration, the natural dose point is made to fall on a dose curve "regenerated" from a sample which has had its TL reset in the laboratory. In this procedure, the regenerated curve indirectly models the missing part of the (N+dose) curve. It has usually been assumed that the shape of this curve is independent of (or at least is not strongly dependent on) the radiation and bleaching history of the sample. Although this is not necessarily true, the procedures described below go some way towards testing this assumption.

In the additive method, extrapolation gives satisfactory results provided that the dose response curve is not too different from linear. However, the uncertainties involved in the extrapolations make it unsuitable when the dose curve is approaching saturation. Berger (1990), Berger and Huntley (1986), Berger et al (1987), Franklin (1986), Franklin and Hornyak (1989), Grün and MacDonald 1989, Grün and Rhodes (1991), Poljakov and Hütt (1990) and Scott and Sanderson (1988) have discussed statistical strategies for determining the uncertainty in extrapolation and measurement strategies for minimising this uncertainty.

An approach with a somewhat different philosophy was originally suggested by Valladas and Gillot (1978) for quartz that had been reset by heating. Faced with saturating dose curves, they used the shape of the second-glow dose curve to model the missing continuation of the first-glow dose curve for doses less than the natural dose N, making allowance for a change in sensitivity after heating.

Readhead (1982) and Smith (1983) made similar suggestions for describing the shape of the dose curve for sediments, where the resetting mechanism is exposure to sunlight. Readhead (op cit) added doses to samples that had been bleached in the laboratory, while Smith (op cit) suggested adding doses to sediments in the same sequence, but of younger age. By a variation of this argument, the growth curve of a zero-age sample (perhaps taken from the surface) may be used (Readhead, 1984). In these methods sufficient overlap is arranged between the (N+dose) curve and the regenerated curve so that the two can be made to coincide by shifting along the dose axis. It can then be determined whether the two sets of points are consistent with a single curve. If they are, then the two data sets jointly define the shape of the complete dose curve.

For some time the Adelaide TL laboratory has been using versions of these procedures which were first described by Readhead (1982; 1984) and Prescott (1983) and subsequently used by them for dating (see, for example, Readhead 1988; Tejan-Kella et al, 1990). More recently, the method has been developed further in conjunction with a programme to test thermoluminescence dating against other geological evidence (Huntley et al, 1993). It is the purpose of the present note to set out the principles and practice of the method, together with an indication of modifications that may be suggested by differing circumstances.

Applying the method

At least twenty 5mg aliquots of prepared sample are given a variety of doses and their TL is used to define the (N+dose) growth curve. A further twenty are given a full sunlight bleach of 12 hours and then given a variety of doses (B+dose). These two curves define the (N+dose) and (B+dose) curves shown in fig 1. If all is well the two curves are the same except for a shift along the dose axis, in which case the (B+dose) curve is now used as a pattern for the missing part of the (N+dose) response. This represents the growth of the TL with radiation dose from the level to which the sample was originally reset at the time of deposition (point M in figure 1). If the sensitivity is not changed by the laboratory bleaching, and if the TL measured after such bleaching is the same as the TL that would have been obtained were it measured just after deposition, then displacement along the dose axis by an amount equal to the equivalent dose will bring the two curves into coincidence.

In practice, the possibility of a sensitivity change must be tested for and, also, the difference between the laboratory-bleached and depositional TL. These are further discussed below. We have used two somewhat different statistical techniques to obtain the dose shift from the data: weighted least squares and maximum likelihood. We describe the most recent versions.

To fit the (B+dose) data we use a single saturating exponential with the optional addition of a linear term which may be necessary in order to accommodate a steady increase at the largest doses. The saturating exponential is widely found to fit dose growth curves and is discussed in most of the references already quoted. Chen and Kirsh (1981), Huntley et al (1988) and Levy (1989) have shown that the function is an appropriate one, at least in some circumstances. Levy (op cit) also shows that an additive linear term can take account of the creation of new trapping centres. Berger (1990) has specifically discussed the use of an exponential-plus-linear model for TL and Grün (1990) has done so for

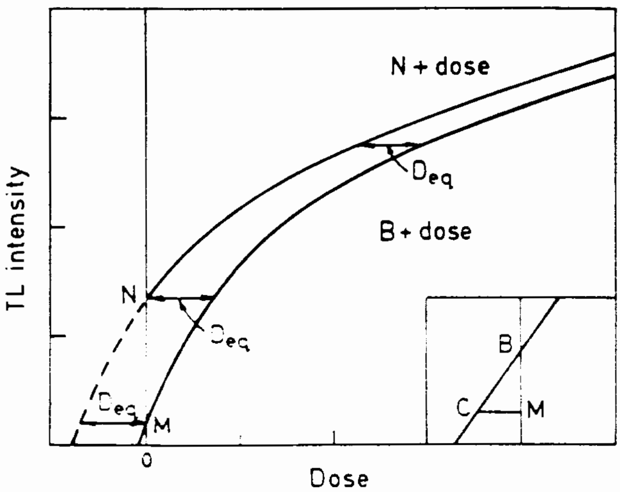

Figure 1.
Schematic diagram illustrating the "slide" method used for finding equivalent dose, D_{eq}. The inset shows the method of correcting for a possible difference between laboratory (B) and natural bleaching (M).

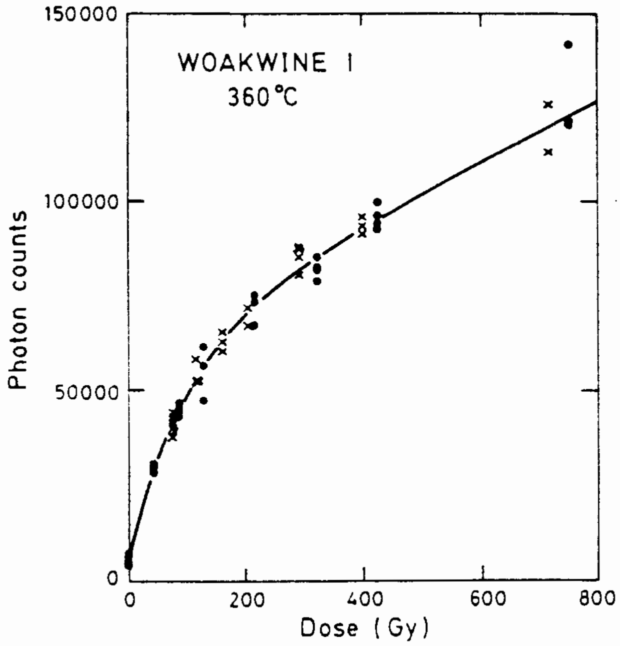

Figure 2.
Dose curve for quartz sediment from the Woakwine I Range. Crosses define the (N+dose) data set of 30 points including 10 at zero dose; dots define the (B+dose) data set of 32 points. The two data sets have been made to coincide by sliding them one with respect to the other by an amount equal to the equivalent dose D_{eq}, which is estimated by least squares or maximum likelihood. The age is about 130 ka.

ESR. We have found that this model is satisfactory over a wide range of samples. It should be noted that both components of the model have an underlying physical basis.

It is worth remarking that the "slide" method which we are describing does not depend on the particular model chosen. The thing that matters is the shape of the curve and a polynomial fit could be used to represent it, as advocated by Readhead (1984).

Our fitting function can be written:

$$I = I_a\{1 - \exp(-(D - D_i)/D_o)\} + k(D - D_i)$$

where,
I is the TL intensity, D is the laboratory dose, I_a is the high-dose asymptote of the saturating exponential, D_i the dose intercept; D_o and k are the scale parameters for the exponential and linear terms respectively.

The first step is to fit this function to the (B+dose) data and initial estimates of the parameters are obtained. This fit is with a least squares routine and a weighting chosen to reflect the assumption of a constant relative standard deviation at all doses. This function is then used as a first approximation to a least squares fit of both the (B+dose) and (N+dose) data sets taken together. In this fit there is an additional parameter, a shift along the dose axis for the (N+dose) data and, optionally, a TL intensity scaling factor.

In our experience (which may not be echoed in general) we have found that only rarely is the scale factor statistically different from unity. Bleached samples differ in this respect from heated samples of the same material. We note that Readhead (1988) reported sensitivity changes in some cases where artificial light sources were used for bleaching. When the intensity scaling factor is not statistically different from unity we set it at unity and re-run the programme. In this case we infer that the data points of the (N+dose) and (B+dose) belong to the same statistical population and can be jointly fitted to the same curve in order to estimate the parameters. This is statistically more efficient. The fitting routine gives the mean square deviation of the data points from the final fitted curve; and the uncertainty in the dose shift is found by a search in reduced chi-square space (Bevington 1969).

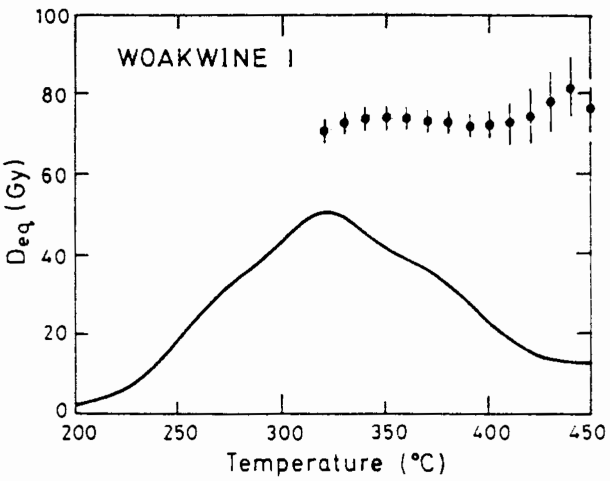

Figure 3.
Equivalent dose plateau for the Woakwine I sample shown in figure 2. The natural glow curve is included to an arbitrary scale.

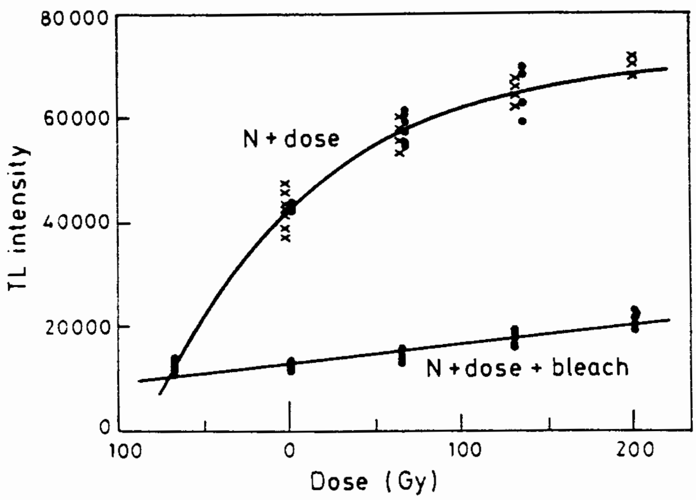

Figure 4.
Modified Partial Bleach procedures applied to quartz sample TC2S/185 from aeolian infill of a fault scarp near Tennant Creek. The TL age is 50 ka. Crosses define the (N+dose) data set; dots define the (B+dose) and (N+dose+bleach) data sets. The two lowest plotted points each contain ten values, unresolved on the scale of the figure. As for figure 2, the first two of these data sets have been jointly fitted to a common curve by sliding. The lowest curve is a linear fit to the (N+dose+bleach) data.

Starting from the same premises and using the same model we have also used maximum likelihood to estimate the same parameters. The uncertainties in the parameters are found by inverting the Hessian matrix. A variety of comparisons show that there is very little difference between the least squares and maximum likelihood analyses. Which to use is, perhaps, a matter of personal preference.

Total bleach

We first discuss the application of the method to a coarse-grain quartz sample to which the total bleach method can be applied. Partial bleach requires some modifications (see below). Selective bleach (Prescott and Purvinskis, 1991) which, like partial bleach, is needed when the degree of resetting is unknown or uncertain, calls for significantly different procedures which are the subject of a separate paper.

An example from the Woakwine Range in South Australia is shown in figure 2, adapted from Huntley et al (1993). The above procedure was applied at 10°C intervals to produce "plateau" graphs of D_{eq} vs T such as shown in figure 3 which is from the same sample.

As mentioned above, the dose shift is a close approximation to the equivalent dose D_{eq} and, under the usual assumptions of total bleach, the two would be identical. It may be necessary to make some adjustment to allow for the fact that the laboratory bleach may have brought the TL intensity to a larger or smaller value than the natural bleach.

Such an improvement in the estimate of D_{eq} can be obtained by using a modern sample from the same geological sequence, e.g., from the surface of an active dune, and assuming that its TL represents the intensity that would have been obtained from the sample being dated had it been measured immediately after its deposition. This measurement is used to make a correction, which is of the order of a few percent, by adding or subtracting a correction to the dose shift, as shown in the inset to figure 1. B represents the TL measured after a laboratory bleach, and M that from a modern dune. In the illustration the laboratory bleach was a little too short and the correction MC is added to the main shift.

Partial Bleach

The above ideas can be used to improve the partial bleach method by reducing the uncertainty in the extrapolation. Fig 4 illustrates the steps. The data are from quartz sample TC2S/185 from the aeolian infill of an earthquake fault near Tennant Creek, Australia. The composite (N+dose) curve is obtained in the same way as the one we have been discussing. The curve marked (N+dose+bleach) has received a partial bleach of thirty minutes which has removed the easily-bleachable component of the TL. In the conventional application of the method, the equivalent dose is marked by the intersection of these two curves, which, it will be remarked, would ordinarily both have been extrapolated.

The fitting procedure already described defines the (N+dose) curve to an extent that negligible extrapolation is necessary for that curve. For the (N+dose+bleach) curve the same procedure could be followed viz, to construct a regenerated curve to use as a model for the partially bleached set. However our experience shows that, as in the present case, the partially bleached curve is often very nearly straight, at least for quartz--a result found by others, e.g. Franklin et al (1992). In these circumstances the practical extrapolation errors from this curve are relatively small and the extra work can probably be foregone. It is worth noting that an exponential fit to the (N+dose+bleach) curve gives no better fit to the data of figure 4 than does the linear.

Perhaps a fitting end-note to justify the present procedures is that, if the (N+dose) data are fitted in the "usual" (i.e. non-composite) way and extrapolated, the estimate of D_{eq} is 30% larger.

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