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Quartz-based optical dating of Weichselian coversands from the eastern Netherlands

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Abstract

Optical dates are presented for Quaternary aeolian coversand units which are separated by the Usselo Layer (Allerød Interstadial). The dates, which were generated using the sand-sized quartz fraction of the sediments, are in direct agreement with geological expectation and indicate considerable potential of the optical method for dating similar Weichselian coversand sequences throughout NW Europe. The intrinsic advantage of the optical dating method over conventional thermoluminescence (TL) dating of sediment lies in the rapidly sunlight-bleachable nature of the optical dating signal, namely optically-stimulated luminescence (OSL). This advantage over TL is demonstrated by an artificial bleaching experiment.

Introduction

The aeolian coversands of Weichselian age mantle Quaternary and older deposits of northwestern Europe over an area of tens of thousands of km^2 (Niessen et al. 1984). Furthermore, they represent significant, widespread lithostratigraphic marker horizons throughout the region (e.g. Kolstrup 1980, Koster 1988). Precise chronostratigraphic control on these strata, and correspondingly the exact timing of phases of increased aeolian activity has therefore been of considerable interest to Quaternary scientists, but has only recently become available with the application of new techniques such as thermoluminescence (TL) dating (e.g. Bluszcz & Pazdur 1985, Kolstrup & Mejdahl 1986, Kolstrup et al. 1990, Dijkmans et al. 1988 1991).

The application of these new dating methods has not however been without problems (e.g. Dijkmans & Wintle 1991). In particular, it has been reported (e.g. Bluszcz & Pazdur 1985, Dijkmans & Wintle 1985 1991, Dijkmans et al. 1988) that the potassium feldspar and quartz fractions of the sands are unlikely to have received sufficient optical bleaching during deposition to reset fully the previously accumulated TL signal to a low, residual level (see later). To overcome this difficulty Dijkmans et al. (1988) applied the plateau method of equivalent dose evaluation for partially-bleached sediments (Mejdahl 1988), achieving some degree of success; Dijkmans & Wintle (1991) reported 'apparent' TL ages which increase systematically with depth although underestimating true age by about 20–40% (see Table 2).

A more elegant approach to dating these partially-bleached sediments is now available following the recent development of the related optical dating method (Huntley et al. 1985, Godfrey-Smith et al. 1988, Smith et al. 1986 1991). As the optical dating method uses only the portion of the total TL signal that is bleachable by daylight, a low or negligible residual would be anticipated upon deposi-

tion and hence the difficulties encountered in evaluating the residual signal level during TL dating are circumvented.

This paper uses optical dating to evaluate the age of cold-climate aeolian sediments which may have been only partially bleached during deposition. The Dutch coversands represent an ideal situation for testing optical dating as their age has been estimated by a number of independent, direct and indirect dating methods (e.g. Hammer et al. 1986, Van der Hammen & Wijmstra 1971).

Following a description of the sampling locality, a brief outline of the optical dating method as applied to quartz will be presented, along with a discussion of the optical bleaching characteristics of quartz separates from the coversands, and their optical dates.

The coversands samples

Two coversands samples from an archaeological section in the Lutterzand area, eastern Netherlands (Fig. 1) were collected for luminescence dating in 1985. At the typesite of the Tjonger culture in the Netherlands, a pit was excavated in which the Usselo Layer (10 cm in thickness) was clearly recogniseable, intercalated within Younger Coversand. The samples were collected 1.2 m above (OX_{OD}715C1; Younger Coversand II) and 1.35 m below (OX_{OD}715D1; Younger Coversand I) the Usselo Layer. They will be referred to as sample C1 and D1 in this text.

The Usselo Layer, a thin (4–10 cm) grey to black organic horizon, has previously been correlated with the Allerød Interstadial (Late Glacial) and assigned an age, based on radiocarbon dates of 11,630 ± 90 BP (GrN 4899) and 11,630 ± 65 BP (GrN 4900) (Van der Hammen & Wijmstra 1971). The Usselo Layer separates the Younger Coversand deposits I and II. The stratigraphic and palaeoclimatic significance of the phases and timing of the aeolian activity, their punctuation by the Allerød Interstadial, and the subsequent Younger Dryas – Pre-Boreal (Pleistocene – Holocene) transition have been the subject of a number of recent investigations (see Koster 1988).

Optical dating

The optical dating method

Optical dating is closely related to TL dating (see Aitken 1985) and, like the latter, it can be used to determine the time which has elapsed since detrital mineral grains from sediments were last exposed to sunlight. A range of sediment size fractions and mineral types have previously been used in TL and optical dating but as sand-sized quartz grains were used in this analysis, discussion is restricted to quartz.

The essential basis of luminescence dating can be expressed by the equation:

$$\text{age} = \frac{\text{natural luminescence}}{(\text{luminescence sensitivity}) \times (\text{annual radiation dose})}$$

where natural luminescence refers to the observed natural sample luminescence acquired due to exposure to ambient natural radioactivity during burial; luminescence sensitivity (or luminescence yield per unit radiation dose) is measured after exposing a portion of the sample to a known dose of radiation from an artificial radioisotope and annual radiation dose received by the sample is due to the alpha, beta and gamma radiation from the K, U, and Th radioactive decay series in its immediate proximity, and a cosmic ray contribution.

The basic concepts of TL dating have been known for some time (e.g. Fleming 1970, Zimmerman 1971), as has the application of TL dating to unburnt sedimentary materials providing that an adequate exposure to sunlight has occurred during the deposition of the sediments (e.g. Wintle & Huntley 1982, Singhvi & Mejdahl 1985, Singhvi & Wagner 1986). The most recent development in luminescence dating has been the use of optical (instead of thermal) excitation sources to stimulate the luminescence signal (Huntley et al. 1985, Smith et al. 1986 1991, Godfrey-Smith et al. 1988). The considerable advantage of these new optical methods is that only light-sensitive portions of total sample luminescence, that is the optically-stimulated luminescence (OSL), are measured and the un-

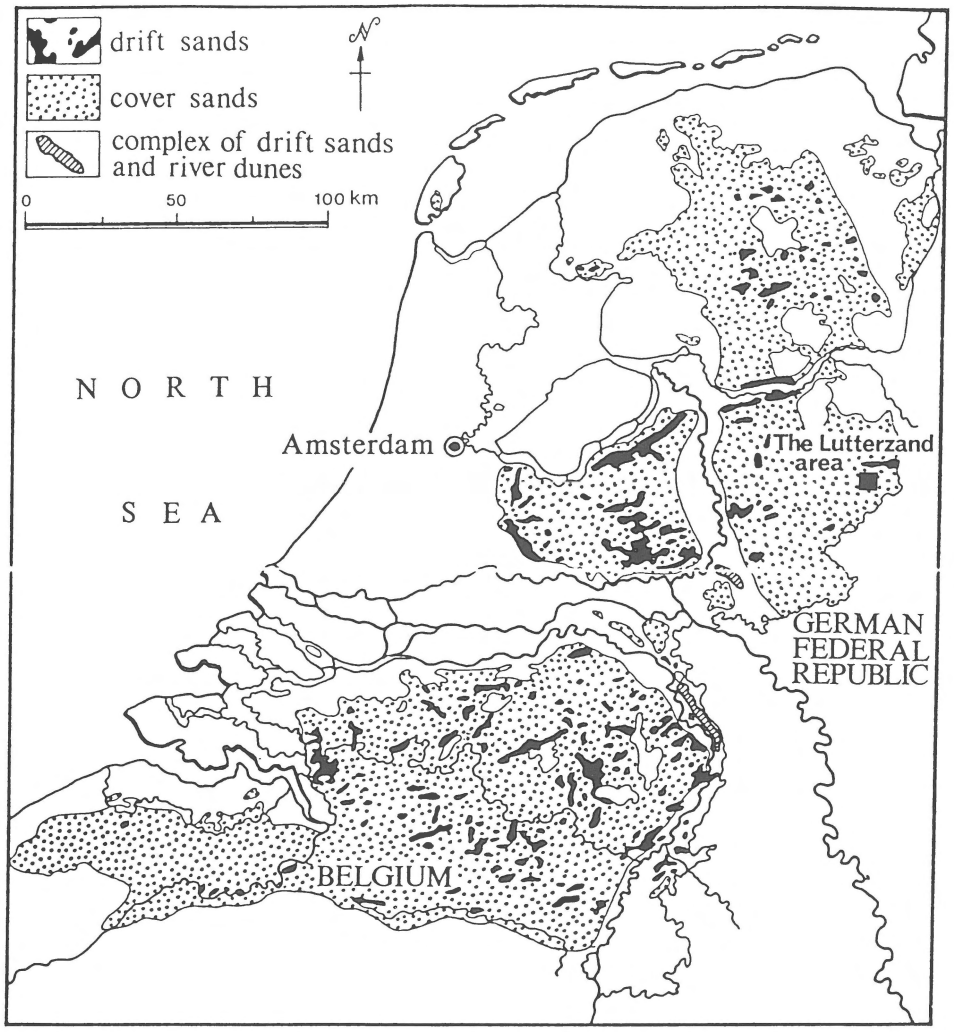

Fig. 1. Map showing the location of the coversand section which was sampled from the Lutterzand area (redrawn from Dijkmans et al. 1988).

bleachable residual luminescence is very much smaller than that encountered in TL dating of sediment.

The basis of optical dating is the same as that for sediment TL dating and the luminescence signals used in each method are closely related (Smith et al. 1986, 1991). When a quartz sample is exposed to light as the grains are deposited, the TL and OSL are reduced to a lower level, which depends on the conditions and duration of light exposure (Fig. 2). In the laboratory it is possible to simulate this process by exposure of the sample to optical (light) energy. Alternatively thermal (heat) sources may be used to completely remove sample TL or OSL. When exposed to either of the above excitation sources, there is photon (light) emission in a range of both visible and non-visible wavelengths (termed thermoluminescence (TL) or optically-stimulated luminescence (OSL) respectively). This arises from recombinations of electrons which had previously been moved into higher energy metastable locations in the crystal lattice by ionising radiation. The quantity of metastable (trapped) electrons is directly proportional to the radiation

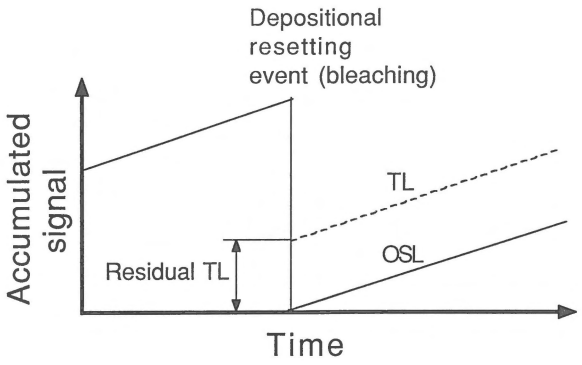

Fig. 2. A schematic representation of the time dependent accumulation of TL and OSL in unburnt, solar-reset sediment. At the hypothetical resetting event note that the OSL signal reduces to near-zero level whereas the TL may retain a significant residual component. If measured at some later stage, effectively all the OSL is the result of post-depositional exposure to radiation. In the case of TL dating, the residual TL level at deposition must be estimated and subtracted from the total TL.

dose which grains have received since last exposed to light, plus a residual quantity responsible for the 'difficult-to-bleach' luminescence.

In addition to the residual level being lower for OSL, another major advantage of the new optical dating method over conventional TL dating of sediment is that the residual level is reached following periods of light exposure as brief as a few minutes. Therefore, an almost instantaneous resetting event in the sediment depositional history, resulting in a minimal residual, is more likely than for TL dating. In TL dating, considerable efforts are expended on assessing the likely residual level down to which the given sample might have been bleached (e.g. Dijkmans et al. 1988, Mejdahl 1988, Singhvi & Wagner 1986) but despite these efforts uncertainties are introduced into the TL dates.

Other advantages of the optical dating method over TL dating include: much improved signal-to-noise ratios during measurement (in particular as a result of the avoidance of black body radiation and thermal quenching); considerably greater precision and ease of aliquot-to-aliquot normalisation; and, speed of sample processing (Rhodes 1990, Smith et al. 1991, Stokes 1991).

Sample preparation

Routine separation procedures were used for the isolation of the coarse-grained (90–150 μm) quartz fraction (Aitken 1985, Smith et al. 1986, Stokes 1991). A portion of each sample was wet-sieved (retaining the 90–180 μm fraction), treated with hydrochloric acid, hydrogen peroxide, and density-separated using a concentrated sodium polytungstate solution (density = 2.70 gm cm^{-3}) to remove heavy minerals. Treatment with hydrofluoric acid followed, resulting in concentration of the quartz grains. Purity of the etched quartz separate was evaluated by testing sample aliquot response to infrared-stimulation (Stokes 1991). The prepared samples were dry-sieved (retaining the 90–150 μm fraction) and mounted onto 10 mm dia. stainless steel discs using 'Silkospray' silicon spray. All preparation took place under subdued red light illumination.

The optical excitation source

The excitation beam used for equivalent dose evaluation was obtained from an argon-ion laser (Coherent Innova 70-2) tuned to an emission wavelength of 514.5 nm. It was operated so that the power reaching the sample was approximately 40 mW cm^{-2}, and the samples were maintained at a temperature of 17° C. A filtered (11 mm of Corning 7-51 signal pass filter and 2 mm of Schott BG-39 red fluorescence rejection filter) EMI photomultiplier (type 9635Q) detected the sample photon emissions. The resulting electronic signal was amplified and fed into a PC-compatible microcomputer for processing. For determination of the equivalent dose (see below), aliquots of sample were exposed to the laser for a period of 30 seconds, following various exposures to a ^{90}Sr-^{90}Y beta irradiation source.

Equivalent dose evaluation

Evaluation of the equivalent dose (ED), or total accumulated radiation dose, was undertaken using

the so-called additive dose method which was initially developed for TL dating (Fleming 1970). In this method, the natural (as found) level of luminescence is measured for a number of sample aliquots and compared with the level of OSL of artificially-dosed sample aliquots. The negative intercept of the x-axis of the resulting best fit curve is the dose of radiation equivalent to that which the sample received since deposition (see Fig. 5).

Final ED estimates are based on the OSL integrated over the full duration of laser illumination, although EDs were calculated for progressive intervals throughout the duration of laser illumination. This so-called 'ED Plateau' is generated to confirm that an adequate amount of bleaching of the dating signal took place during deposition; to ensure that accidental bleaching during sampling or processing did not take place; and other factors relevant to the dating method (Aitken 1991).

After artificial laboratory doses have been administered, a portion of the trapped electrons occupy sites within quartz crystals where they are unlikely to remain over geological time due to their high probabilities of eviction at ambient temperatures. As this charge population has already been lost from the natural samples, it also needs to be removed from dosed aliquots so that only geologically-stable electrons remain trapped. For quartz, this is achieved by pre-heating the sample aliquots at a temperature of 160° C for a duration of 16 hours (Stokes 1991).

Normalisation of the sample aliquots was attempted by both the natural and the dose normalisation methods (Smith et al. 1986, Rhodes 1990).

Annual dose evaluation

The radiation dose received by a sample is derived from the decay of adjacent radioisotopes within a sphere of radius 30 cm, and the cosmic ray contribution. The wide ranging influence of the radioisotopes necessitates either some form of on-site dosimetry, or the sampling and laboratory analysis of material only from suitably homogeneous strata which are considered representative of the complete sphere of radioactive influence. The coversand samples were collected from homogeneous beds in excess of one metre in thickness and their radioactivity was measured by laboratory methods only. Because the various laboratory-based methods for evaluation of annual dose are differently affected by radioactive disequilibrium, the use of a combination of methods in parallel is typically recommended as a test of the reliability of results (Aitken 1985). The evaluation of the annual dose of radiation was undertaken by two independent sets of methods, namely, (i) thick source alpha counting and flame photometry, and (ii) high resolution gamma spectroscopy.

Thick source alpha counting is a relatively rapid and highly sensitive method of determining a sample's U and Th content based on sample alpha particle emission. In this study, approximately 3 g of crushed (< 38 μm) unsealed sample was spread over a 42 mm diameter ZnS scintillation screen positioned on a calibrated photomultiplier coupled to suitable counting electronics and counted following a delay of two weeks. After unsealed counting, the samples were sealed and re-counted to test for emanation of radon. The routine analytical chemical technique of flame photometry was used for the determination of the potassium content. Approximately 100 mg splits of the crushed alpha counted samples were used for this purpose.

High resolution gamma spectroscopy is a method which allows the direct measurement of individual members of the uranium and thorium series in addition to potassium. The advantage of this approach is that it provides data on the equilibrium status of the uranium and thorium decay chains which may provide an insight into any changes in the annual dose resulting from the post-depositional input or leaching of radioisotopes (Murray & Aitken 1985). In this study, approximately 40 g of sample was sealed within an epoxy resin, stored for a period of at least four weeks, and counted using a liquid nitrogen-cooled intrinsic germanium-type detector.

For details of the above methods readers are refered to Aitken (1985) and references therein. The results of the annual dose determinations are presented (see Table 1) along with the ED eval-

uations and calculated ages following a discussion of the bleaching characteristics of the samples.

A comparative test of residual luminescence levels

The reliability of any luminescence date depends in part on the assumption of complete bleaching of the previously accumulated luminescence upon redeposition. Where complete signal zeroing is not the case, the probable level of the residual at the time of deposition must be estimated and its contribution subtracted from the experimentally calculated ED (e.g. Mejdahl 1985 1988). An assessment of the level of resetting may be achieved either by evaluating EDs for sediments from analogous modern depositional settings (e.g. Prescott 1983, Stokes 1991), or alternatively, by undertaking bleaching studies on the sample to be dated (e.g. Singhvi & Wagner 1986). As a result, a residual signal level for some geologically-realistic duration of bleaching may be estimated (e.g. Singhvi and Wagner 1986, Dijkmans et al. 1988).

As a test for the degree of bleaching of the luminescence signals and the suitability of the optical dating method for the Dutch coversand samples a series of aliquots of sample C1 were exposed to dull daylight (i.e. a cloudy mid-September afternoon in Oxford) for times ranging from one minute to four hours. The degree of signal loss was calculated by comparing the OSL and TL levels remaining with unbleached aliquots (after normalisation). The results of the experiment can be seen in Fig. 3. The OSL signal is reduced to less than 5% of the original signal in five minutes, and to less than 1% in ten minutes. By contrast, the TL signal is unaffected by exposures of less than 30 minutes, and even after four hours, a residual level in excess of 40% is apparent. These findings support those of Dijkmans et al. (1988) who found a quartz TL residual

Table 1. Sample radioactivity and annual dose determinations.

Method/measurement	Sample	
	C1	D1
A. Alpha counting and flame photometry		
Total alpha count (ks^{-1})†	1.85 ± 0.04	1.47 ± 0.03
Ratio (sealed/unsealed)	1.06 ± 0.04	1.20 ± 0.04
Dry $D_{\beta(U.Th)}$ (Gy ka^{-1})	0.15 ± 0.03	0.11 ± 0.03
Dry $D_{\gamma(U.Th)}$ (Gy ka^{-1})	0.15 ± 0.01	0.12 ± 0.01
K_20 (%)	0.86 ± 0.04	0.87 ± 0.04
Dry $D_{\beta(K)}$ (Gy ka^{-1})	0.59 ± 0.03	0.60 ± 0.03
Dry $D_{\gamma(K)}$ (Gy ka^{-1})	0.18 ± 0.01	0.18 ± 0.01
Dry D_{β} (Gy ka^{-1})	0.74 ± 0.04	0.71 ± 0.04
Dry D_{γ} (Gy ka^{-1})	0.33 ± 0.01	0.30 ± 0.01
Wet D_{total} (Gy ka^{-1})¶	1.11 ± 0.06	1.03 ± 0.06
B. High Resolution gamma spectroscopy		
Dry $D_{\beta(U.Th)}$ (Gy ka^{-1})	0.09 ± 0.01	0.10 ± 0.01
Dry $D_{\gamma(U.Th)}$ (Gy ka^{-1})	0.10 ± 0.01	0.12 ± 0.01
Dry $D_{\beta(K)}$ (Gy ka^{-1})	0.60 ± 0.02	0.61 ± 0.02
Dry $D_{\gamma(K)}$ (Gy ka^{-1})	0.18 ± 0.01	0.18 ± 0.01
Dry D_{β} (Gy ka^{-1})	0.69 ± 0.02	0.71 ± 0.02
Dry D_{γ} (Gy ka^{-1})	0.29 ± 0.01	0.30 ± 0.01
Wet D_{total} (Gy ka^{-1})	1.00 ± 0.07	1.03 ± 0.07

† alpha counting (screen diameter = 42 mm) undertaken on unsealed, crushed (< 38 μm) samples. Conversion of the measurement data to annual dose rates is based on equations from Aitken (1985 1990).

¶ assuming a $D_{cosmic} = 0.185 \pm 0.01$ Gy ka^{-1}, and using an insitu moisture content of 17 ± 5% and a saturation water content of 40% (as measured in the laboratory).

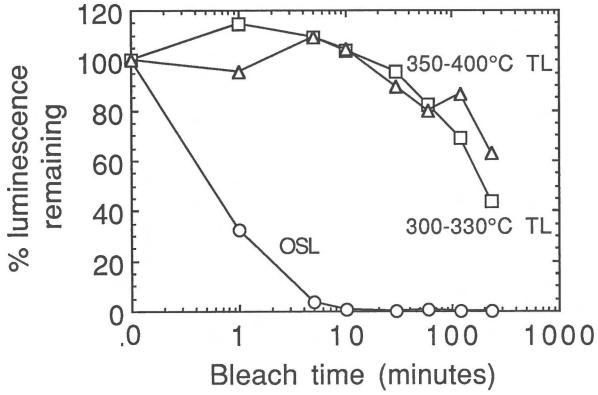

Fig. 3. Loss of TL and OSL for sample C1 as aliquots are exposed to progressively longer durations of daylight (as on a dull cloudy Oxford afternoon). The OSL signal is seen to reduce rapidly to less than 5% of its initial level within 5 minutes. By comparison, both low and high temperature regions of the TL signal remain at significant levels (40%) even following 4 hours of daylight exposure.

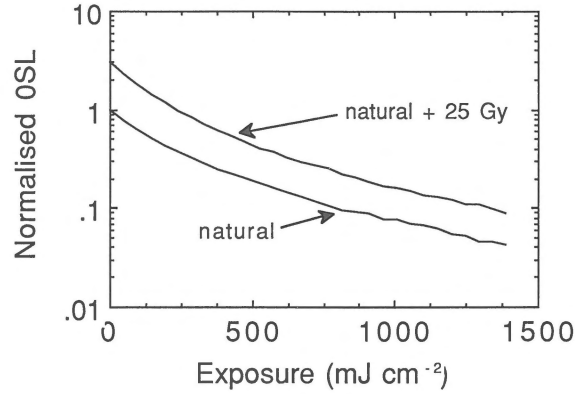

Fig. 4. Loss of optically-stimulated luminescence (OSL) as aliquots of sample C1 are exposed to the 514 nm line of an argon-ion laser.

level of approximately 25% of the original TL following an equivalent natural sunlight exposure of 120 hours using a SOL 2 solar simulator.

It is apparent from Fig. 3, as anticipated from experiments using other quartz samples and from other investigations (Godfrey-Smith et al. 1988), that there is a considerable advantage in using the optical dating approach over conventional TL dating (e.g. Dijkmans et al. 1988) for age evaluation of the coversand deposits. The 'geological likelihood' of daylight exposures of the the order of a few minutes being considerably more realistic than 120 hours, and the actual residual levels for the OSL and TL at those durations of exposure both emphasise this advantage.

The optical dates

All sample aliquots exposed to the laser exhibited the characteristic rapidly decaying OSL signal as the light-sensitive electron traps depopulate (so called 'shine down curves', e.g. Fig. 4). Addition of radiation to the natural samples caused no change in the shape of the OSL decay curves (Fig. 4), and the integrated OSL counts for any given exposure interval, or as calculated for the total duration of laser exposure, when expressed as a function of added radiation dose exhibit a linear growth with dose (e.g. Fig. 5). Such OSL growth curves are directly analogous to TL growth curves and are used to evaluate the ED.

As both samples exhibited a considerable change in sensitivity with dose due to the experimental procedures, dose normalisation was not possible and only the natural normalisation method, which measures the relative intensities of sample aliquots prior to dosing and pre-heating, has been employed. Such changes in sensitivity do not negate the dating procedure or affect the dating results when using the natural normalisation method (Smith et al. 1991, Stoneham & Stokes 1991). The EDs were calculated using a linear least squares fitting algorithm for progressive intervals of laser exposure, and by integrating the OSL over a total illumination of 1.2 J cm^{-2} (Fig. 5). The use of the total luminescence results in the smallest error term relating to the counting statistics. As a result the final quoted EDs were evaluated using the total laser exposure. EDs of 11.4 ± 1.2 and 13.6 ± 2.3 Gy were calculated for samples C1 and D1 respectively.

When these are divided by the annual dose of radiation (as calculated using the high resolution gamma spectroscopy data and corrected for moisture attenuation (Table 1)), ages of 11.4 ± 1.4 and 13.2 ± 2.4 ka are obtained. The final error terms in the age evaluations represent the combined systematic and random uncertainties in both the OSL

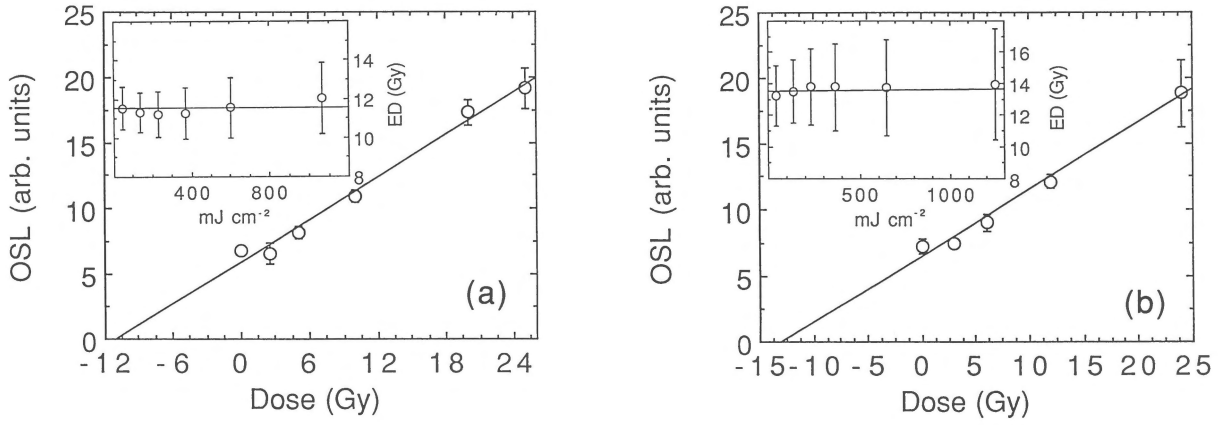

Fig. 5. Growth of OSL signal with added laboratory dose for samples C1 (a) and D1 (b), using integrated signal observed during a laser exposure of 1.2 J cm^{-2}. The inset shows the ED evaluated for progressive intervals of the laser exposure (using a similar plot as for the integrated signal). Four aliquots of sample were used per additive dose point and six sample aliquots were used to measure the natural OSL signal level.

data and dosimetry, calculated after Aitken & Alldred (1972).

Discussion

Excepting the TL age estimates, the optical dates are in good agreement with alternative dating techniques (Table 2). The age of 13.2 ka for sample D1 could perhaps indicate the sampling of an Older Coversand unit rather than the inferred Younger Coversand I and a hiatus within the sequence. The large (± 18%) errors quoted for D1 do however encompass the age range of Younger Coversand I deposition.

TL dating of the fine-grained and potassium feldspar fractions of these same (Aitken et al. 1986) and similar (Dijkmans et al. 1988, Dijkmans & Wintle 1991) coversand samples would appear to underestimate the true age of the units. The underestimations of the TL dates could be the result of a number of factors including overestimation of the residual level of TL at the time of deposition; the possibility of long term fading of the luminescence signal of some of the mineral species present in the polymineral and feldspar sample populations; or in the case of the fine grain dates the downwards infiltration of stratigraphically higher, and younger, aeolian silts (e.g. Pye 1983).

As only two optical dates are presented here, any implications must be considered tentative. It should be stressed however that ongoing quartz optical dating of chronologically well-constrained sequences (e.g. Smith et al. 1991), and the validation of effectively complete resetting of OSL upon deposition for a selection of modern depositional settings (e.g. Stokes 1991), provide strong support for the dates generated for the coversands.

Some discussion of the high resolution gamma spectrometer results is warranted as a possible secular disequilibrium within the uranium chain is noted in each of the samples dated (Table 3). In considering natural series disequilibria of uranium and thorium it is convenient to study the concentrations of certain key isotopes in groups based on the subdivision suggested by Rosholt (1959). Both samples exhibit an excess of the Group 1 and 2 long-lived isotopes (^{238}U, ^{234}U). As such, the annual dose of U-derived beta and gamma radiation received by the samples may have not remained constant through time.

It is possible that the samples were actually deposited in disequilibrium, or alternatively that the disequilibrium has developed since burial due either to addition of Group 1 and 2 parent isotopes or due to leaching of Group 4 (^{226}Ra). Given the well-drained nature of the sediments, their typically close-to-surface stratigraphic/topographic posi-

tion, and regionally relatively moist conditions, the latter hypothesis is considered as the most likely reason for the disequilibrium. Assuming that all disequilibrium is the result of the migration of daughter products, based on the quantity of missing radioisotopes, the total annual dose may have been up to 5% greater immediately following depositon.

The limited effect of the disequilibria on the combined environmental beta and gamma dose is incorporated within the overall errors calculated for the dates presented. This is due for the most part to the dominance of ^{40}K as the major contributor to the annual dose of beta radiation (Table 1). It shoud be borne in mind however, that no similar index of potassium mobility within the system is available. The agreement between the optical dates and the alternative chronologies (Table 2) would indicate however that if potassium migration has taken place, it has done so only to an unimportant degree.

Conclusions

This paper demonstrates the application of the optical dating method to cold-climate aeolian sands. The major advantage over TL dating is that only light-sensitive portions of the total TL signal are measured. As a result, effectively complete zeroing of previously accumulated OSL occurs upon deposition, the zeroing being caused by exposure to daylight. The OSL measured during the dating analysis is therefore almost entirely the result of the

Table 2. Chronostratigraphy, lithostratigraphy and absolute age determinations of Late Pleistocene Dutch coversands and related deposits.

		Age (ka)				
Chrono-stratigraphy[1]	Litho-stratigraphy[1]	Ice core data[2]	^{14}C[3]	TL[4]	TL[5]	Quartz optical date[6]
HOLOCENE						
Pre-Boreal (IS)	Undifferentiated younger and older driftsands	10.62 ± 0.15			0.2 ± 0.2 1.2 ± 0.2	
PLEISTOCENE						
Younger Dryas (S)	Younger Coversand II	10.7		7.3 ± 1.1	6.2 ± 0.5 6.9 ± 0.5 8.1 ± 0.5 8.7 ± 0.5 8.8 ± 0.5 9.3 ± 1.0	11.4 ± 1.4
Allerød (IS)	Usselo Layer		11.63 ± 0.09			
Earlier Dryas (S)	Younger Coversand I			9.7 ± 2.0	7.9 ± 0.4 11.4 ± 1.5	13.2 ± 2.4
Bølling (IS)	Lower Loamy Bed					
Upper Pleniglacial(s)	Older Coversand II				9.2 ± 0.6 10.3 ± 0.8 11.8 ± 1.0	

1. Stratigraphy after Koster (1988), IS = Interstadial, S = Stadial.
2. After Hammer et al. (1986).
3. After Van der Hammen & Wijmstra (1971).
4. After Aitken et al. (1986) using polymineral fine grains.
5. After Dijkmans et al. (1988) and Dijkmans & Wintle (1991) using potassium feldspar.
6. This study.

annual flux of radiation to which the sample has been subjected since deposition. This contrasts strongly with TL measurements for similar samples (e.g. Dijkmans et al. 1988) which document residual TL levels possibly in excess of 25% of the total natural TL level following extended (>20 hours) sunlight-simulated bleaching.

Optical dates of 11.4 and 13.2 ka have been calculated for samples of Younger Coversand II and Younger Coversand I respectively. The dates are in good agreement with other dating methods and geological expectation. A more regional survey of the coversands of NW Europe will be carried out to test the presently hypothesised contemporaneity of aeolian phases in NW Europe (e.g. Koster 1988) during the Late Pleistocene.

Furthermore, the results indicate that the optical dating method provides a means of absolutely dating the precise timing of actual phases of aeolian activity, thus avoiding the use of dates on associated interstadial features such as the Usselo Layer to provide ages which bracket the aeolian activity.

Table 3. High resolution gamma spectroscopy data. All activities are quoted in Bq kg^{-1}. For details of the procedure see Murray & Aitken (1985).

Isotope used to determine activity	Sample activity	
	C1	D1
^{235}U, ^{234}U	5.65 ± 0.77	6.24 ± 0.85
^{230}Th	3.26 ± 5.80	−1.33 ± 8.03
^{226}Ra, ^{214}Pb, ^{214}Bi	3.87 ± 0.26	4.63 ± 0.28
^{210}Pb	2.72 ± 1.02	4.58 ± 1.13
Average activity U chain	3.97 ± 0.24	4.77 ± 0.26
P (equilibrium)[1]	<30%	30–50%
^{228}Ac	5.99 ± 0.45	6.00 ± 0.46
^{224}Ra, ^{212}Pb, ^{212}Bi, ^{208}Tl	5.73 ± 0.23	6.40 ± 0.25
Average activity Th chain	5.79 ± 0.21	6.31 ± 0.22
P (equilibrium)	50–70%	50–70%
^{40}K	230.01 ± 8.37	232.18 ± 8.59

[1] Probabilities of equilibrium for each chain are calculated based on a reduced chi-squared test:

$$T = \frac{1}{(n-1)} \sum_{1}^{n} \frac{(y_i - y)^2}{e_i}$$

where n = no. of degrees of freedom, y_i = activity values for given isotope group (i), y = average activity for full chain, e_i = error for given isotope group activities.

Such chronologies have for some time been possible by the application of TL dating of sediments (e.g. Juvigne & Wintle 1988), although the application of TL dating to partially-bleached sediments presents inherent difficulties both in TL signal bleachability (e.g. Fig. 3) and in actual TL measurement and normalisation.

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