Technical Memorandum 41

Thermoluminescence dating techniques at the Alligator Rivers Region Research Institute

Richard G Roberts, Christopher J Uren,
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This Technical memorandum was prepared by

Richard G Roberts, Christopher J Uren, Andrew S Murray

Richard G Roberts—Department of Prehistory,
RSPACS, Australian National University, Canberra ACT
Christopher J Uren—Alligator Rivers Region Research Institute
Andrew S Murray—CSIRO Water Research, Canberra ACT

Supervising Scientist for the Alligator Rivers Region
GPO Box 407, Canberra ACT 2601 Australia

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Abstract

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The Alligator Rivers Region Research Institute housed one of five thermoluminescence (TL) dating laboratories operating in Australia. The laboratory was established in 1985 to assist geomorphological research into uranium mining activities in the Region. Dating ceased in 1990 after the TL component of two geomorphological consultancies had been completed (Nanson et al 1990, Roberts et al 1991).

Techniques for dating Quaternary sediments have been developed, with specific application to fluvial and colluvial sand deposits in tropical northern Australia. In TL dating, the age of the deposit is determined as a function of the 'equivalent dose' (ED, the quantity of ionizing radiation required to produce the observed natural TL intensity) and the dose rate (the rate of supply of ionizing radiation at the depositional locale). To determine the ED, we used the 90–125 μm diameter quartz fraction of each deposit (following conventional quartz-inclusion pretreatment procedures) and adopted a combined additive-dose and regenerative methodology, as proposed by Readhead (1984, 1988). For unheated sediments, the TL clock is reset by exposure to sunlight, but an unbleachable (residual) TL signal remains even after prolonged exposure. The residual TL signal at the time of sediment deposition was estimated from ED determinations on modern (surface and near-surface) deposits, again following Readhead (1984, 1988).

The laboratory was at the forefront of TL dating in two respects. First, it was among the first in Australia to examine the potential of dating water-lain deposits by TL. This provided the opportunity to obtain ages for a range of deposits that are widespread across northern Australia and are of particular relevance in assessing the long-term geomorphological stability of uranium mining waste sites. Second, the dose rate was determined by state-of-the-art techniques that were not readily accessible to other TL dating laboratories. Radionuclide concentrations were deduced from high-resolution gamma and alpha spectrometry, which enabled disequilibrium in the uranium decay series to be identified and the time-dependent correction in the dose rate to be applied. The latter was performed using the computer program listed in Appendix A.

Introduction

Thermoluminescence (TL) is the thermally-stimulated emission of light from an insulator or semi-conductor, following the previous absorption of energy from ionizing radiation (McKeever 1985). One of the earliest reported observations of TL was by Robert Boyle in 1663, however the cause of the phenomenon was not understood until 1905. Daniels et al (1953) recognised TL as a potential dating technique, particularly for archaeological artefacts. During the 1960s and 1970s techniques were developed for dating fired pottery (Fleming 1979) and subsequently extended to encompass heated and unheated geological materials (Aitken 1985). Of the latter, windblown loess and desert dune deposits have been dated successfully and water-lain sediments have yielded promising results. State-of-the-art reviews are given by Wintle and Huntley (1982), Singhvi and Mejdahl (1985) and Berger (1988).

The principal of TL can be expressed simply. Most rocks contain minerals, such as quartz and feldspar, which exhibit thermoluminescent properties. These minerals 'trap' energy, in the form of ionized electrons, in imperfections of the crystal lattice. The major sources of the ionizing energy are the decay chains of uranium and thorium, as well as potassium and, to a lesser extent, cosmic radiation (Mejdahl & Wintle 1984). When the mineral is heated sufficiently, the energy stored within the crystal lattice is released as a pulse of light. Once heated (or 'glowed') to emit light, the material must be exposed again to ionizing radiation in order to luminesce when reheated—without further irradiation only the light produced by incandescence (termed 'black-body' radiation) is emitted when the material is glowed. The difference between the first-glow and black-body light levels represents the TL due solely to radiation.

For dating purposes, there must be a mechanism to start the TL 'clock' at time-zero. For pottery fired at 600°C or above, the geological TL signal is erased completely, and the time of firing corresponds to time-zero. When the pottery is glowed subsequently, the TL emitted is a measure of the radiation dose (the 'equivalent dose') accumulated since firing (Fleming 1979). The time elapsed since firing can then be calculated by dividing the equivalent dose by the amount of radiation the pottery would have received from the environment per annum. The radiation dose from the environment over the time since deposition (or the 'environmental dose rate') is difficult to quantify. Especially if the sample is particularly ancient, and must, to some extent, be extrapolated from modern conditions in the sample medium.

The processes by which the TL clock in sediments is reset include volcanic heating, meteorite impact, mechanical grinding, crystallization, and exposure to sunlight or heat (bushfires). Conditions in the Alligator Rivers Region are suitable for sunlight 'bleaching' of fluvial and colluvial sediments as a zeroing mechanism, with the heat generated by bushfires assisting the resetting of the TL clock in colluvial sediments.

Background

2.1 The Alligator Rivers Region

The area known as the Alligator Rivers Region (ARR) of Northern Australia is defined by the catchments of three major rivers: the East Alligator River, South Alligator River and West Alligator River. Within this boundary (fig 2.1) lie the World Heritage listed Kakadu National Park, traditional Aboriginal land holdings and extensive mineral deposits.

Mining in the Region began in earnest during the 1950s when uranium was discovered in the South Alligator River valley. A number of small deposits in this area were mined up until the mid 1960s (Fisher 1969). During the 1970s four major uranium deposits were identified in the Region: the Koongarra, Jabiluka, Ranger and Nabarlek mineral leases. The latter two have been mined, but only the Ranger mine is currently operational.

The mining and milling of uranium ore creates large volumes of low-level radioactive waste: waste rock, below-ore grade uranium material (BOGUM) and mill tailings. The treatment and disposal of this waste is outlined in Guidelines for the implementation of the *Code of Practice on the Management of Radioactive Waste from the Mining and Milling of Radioactive Ores*, Commonwealth of Australia, 1987. A major rehabilitation requirement set out by the Code regards the need for rehabilitated structures to be suitable for the long-term management of waste material. Two time scales are specified: a design life of at least 200 years during which the structure is expected to perform fully in accordance with design objectives and construction specifications, and a *structural life* of about 1000 years during which the structure is expected to retain its integrity and perform its functions adequately.

In order to achieve these objectives, a number of studies have been instigated by the Geomorphology section of the Alligator Rivers Region Research Institute to investigate geomorphological processes in the Region which may compromise rehabilitation requirements. The majority of work has been carried out in the Magela Creek system, a major left-bank tributary of the East Alligator River which contains both the Ranger and Jabiluka deposits in the lower part of the catchment. Thermoluminescence dating has been utilised in some of these studies to determine the age of Quaternary sedimentary deposits and the rates of Quaternary sedimentation processes. This information assists in predicting the long-term geomorphological stability of natural landforms in the vicinity of proposed mine rehabilitation structures.

2.2 Thermoluminescence dating in the Region

Carbonaceous material of the kind used for ^{14}C dating is generally not well preserved in the Region due to the tropical weathering environment and the acidic rainfall. In addition, the high number of bushfires in the Region (during the Holocene at least) has increased the risk of

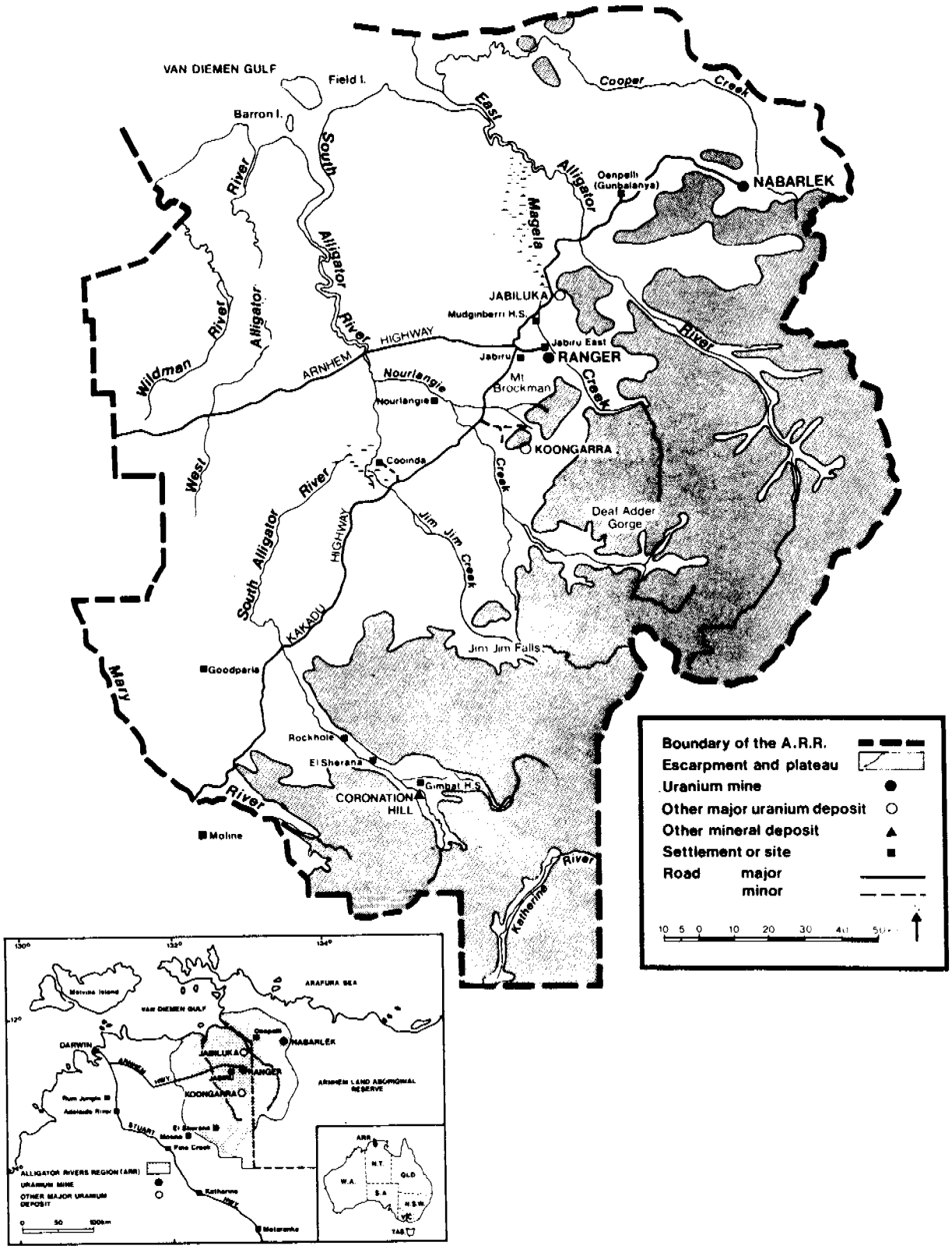

Figure 2.1 Location and physiography of the Alligator Rivers Region of the Northern Territory

contamination for ancient carbon by younger material, resulting in expensive and laborious pretreatment of any ^{14}C sample.

However, the environmental characteristics of the ARR provide conditions ideal for thermoluminescence dating. The geology of the Region produces sediments suitable for both the uptake of radiation from the environment and the subsequent release of this energy in the TL dating procedure. Climatic and geomorphological characteristics of the Region promote adequate bleaching of the sediments prior to burial, such that the moment of burial corresponds with time-zero (section 1).

2.2.1 Geology

The geology of the Alligator Rivers Region is dominated by the Pine Creek Geosyncline and the Arnhem Land plateau. The Pine Creek Geosyncline comprises Lower Proterozoic metasediments overlaying an Archaean basement, and extends from Rum Jungle in the west to Oenpelli (Gunbalunya) in the east. Subsidence of the Geosyncline at 1800 Myr resulted in marked deformation and metamorphism of the sediments, particularly in the north-east, and probably accounts for the high incidence of secondary uranium mineralisation in the Region (Needham, 1988).

The Arnhem Land plateau overlies the eastern part of the Pine Creek Geosyncline. The plateau consists of flat-bedded Carpentarian quartz sandstone 200–400 m thick with minor conglomerates and interbedded basalt flows (Needham 1988). This sedimentary unit, known as the Kombolgie formation, displays a marked unconformity with the underlying Lower Proterozoic material. The plateau rises abruptly from the lowlands of the Koolpinyah surface along a predominantly north-south escarpment. The main weathering products of the sandstone are fine to coarse grained quartz sands, suitable for TL dating. The slow rate of weathering of the sandstone in most areas suggests that the majority of individual sand grains are bleached before removal from the rock-surface. Any grains sheltered from sunlight at this stage may be bleached prior to, or after, deposition on the lowlands by the processes outlined in section 2.2.3.

2.2.2 Climate

The Alligator Rivers Region has a seasonally-wet tropical climate. The Wet season generally occurs between November and March (McAlpine 1976). Almost 90% of the annual rainfall occurs during these months, with January and February recording the highest averages. The Dry season occurs between April and October, and during this time evaporation greatly exceeds rainfall. The 21-year average annual rainfall for Jabiru Airport is 1465 mm. Solar insolation in the Region is high, with little cloud cover during the Dry season. Solar ultraviolet (UV) radiation is particularly effective at bleaching quartz and, for cloudless conditions, the Australasian tropics have an annual UV flux at the ground surface of approximately 1.1 MJ/m^2 (Ilyas & Barton 1983). The UV flux remains high even under a cloudy sky, with the surface dosage being roughly halved by 100% cloud cover (Ilyas 1987).

2.2.3 Geomorphology

All of the major river systems in the vicinity of the four major uranium deposits have headwaters in the Arnhem Land plateau (section 2.2.1). As a result, the rivers characteristically transport sand material as a large proportion of their bedload; sand which is suitable for TL dating (Roberts et al 1991). A typical example of such a river system is the Magela Creek (fig 2.2). Geomorphological research so far has focused on the Magela Creek system, as both the Ranger Uranium Mine and the Jabiluka mineral lease lie within its catchment.

The Magela Creek has a highly seasonal hydrological regime; generating peak discharges in January–March and contracting to a series of unconnected billabongs during the Dry (Galloway

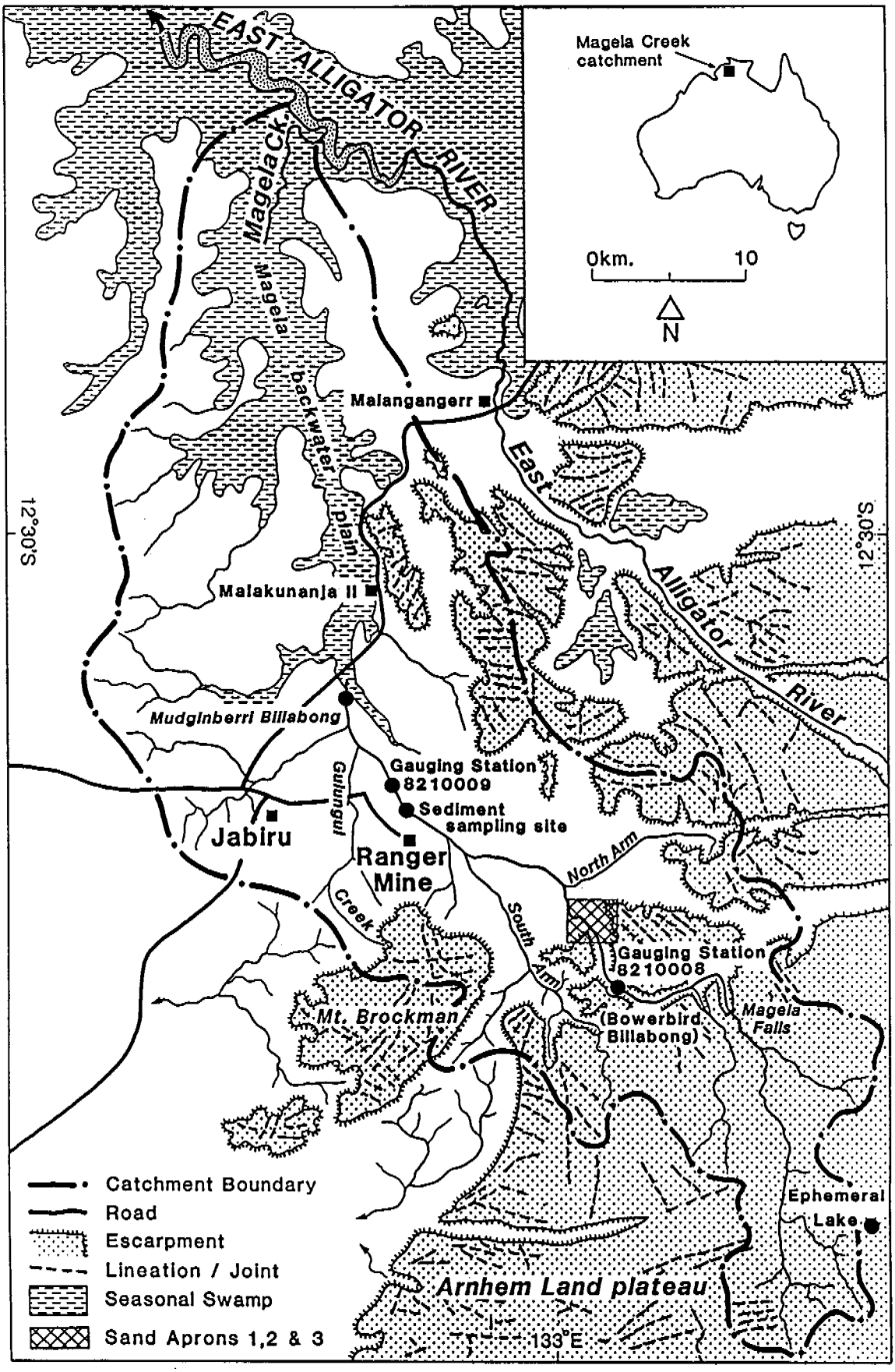

Figure 2.2 Location and physiography of the Magela Creek catchment, showing features relevant to the publications listed in Appendix C

1976). The Magela system drains the Arnhem Land plateau (including outliers) to the south and east of the Ranger Mine and the Koolpinyah surface lowlands which abut the plateau escarpment. From the escarpment to Mudginberri Billabong, the Magela Creek has an anastomosing sand-bed channel located on the western side of a shallow valley incised into the Koolpinyah surface (Nanson et al 1990).

Bedload forms the majority of material transported by the Magela upstream of Mudginberri, and is comprised of sand material derived from the plateau and intermediary sinks (Roberts et al 1991). Hart et al (1987) showed that mean suspended sediment concentrations for Magela Creek water in this sand channel section are typically very low at about 13 mg/L (range 4–59 mg/L). Thus, the majority of the Magela's load is composed of datable quartz-sand material. However, Mudginberri Billabong currently acts as a bedload sink. Downstream of Mudginberri Billabong, the Magela Creek floods out into a large (200 km^2) backwater plain dammed by the levees of the East Alligator River (fig 2.2).

The marked seasonality of rainfall and the annual occurrence of bushfires within Kakadu National Park result in a marked reduction in vegetation cover at the end of the Dry season. The ground surface is thus exposed annually to direct sunlight, promoting bleaching of the surficial sand grains. The TL clock may also be reset thermally, as bushfires in the Region reach temperatures of 300–500°C at the ground surface (Braithwaite & Estbergs 1985). TL dating of colluvial deposits ('sand aprons') in the Magela Creek catchment has shown that they vertically agrade at only 30–70 mm/kyr or 30–70 µm/yr (Roberts et al 1991). The 90–125 µm diameter quartz grains used for TL dating may therefore, lie exposed on the surface for a year or more and experience at least one severe bushfire. Buried sediments are unlikely to be heated to above 100°C (cf Koch & Bell 1980, Skeat et al 1987) and are thus able to store their acquired TL.

Thermoluminescence dating methodology

3.1 Basic principles

Bleaching by sunlight is the relevant zeroing mechanism by which the thermoluminescence (TL) 'clock' is reset in fluvial sediments analysed at the Alligator Rivers Region Research Institute laboratory. However, unlike heating, sunlight does not remove all geological TL, and a small unbleachable 'residual' component (I_0) remains within the mineral grains (Huntley 1985, Berger 1990a). If the TL level at the time of burial can be ascertained, or if the I_0 level was demonstrably attained, then the age of an unheated sample is given by the following relation:

$$\text{Age} = \frac{\text{natural TL} - \text{residual TL}}{\text{dose rate} \times \text{TI per unit dose}} \qquad \text{(Relation I)}$$

where TL is measured in arbitrary units of light output, dose rate is measured in Grays per year (Gy/yr, where 1 Gy equals 1 J/Rg) and the age is calculated in years.

The numerator represents the level of TL acquired since the sample was last exposed to sunlight, whereas the denominator represents the amount of ionizing dose supplied each year from the environmental radiation field multiplied by the rate at which the sample converts this dose into TL. The methods used to determine the four quantities comprising Relation I are discussed below, with specific reference to the dating of quartz.

3.2 Natural thermoluminescence

Natural TL is the light emitted by a sample that has not been bleached or irradiated since excavation. It is obtained by electrically heating the sample from room temperature to ~500°C in an oven filled with a dry inert gas. The luminescence is observed through a photomultiplier tube and recorded as a 'glow curve' of temperature versus TL intensity. The photomultiplier tube is fitted with filters to transmit the wavelengths of emitted light suitable for dating and to reduce the unwanted black-body radiation. The blue-violet part of the electromagnetic spectrum (400–500 nm) is used to date quartz with the 'coarse-grain' (or 'quartz-inclusion') technique.

Quartz grains of 90–125 μm diameter are isolated from the sample, and their α-irradiated outer 10 μm coating is removed (or 'etched') with hydrofluoric acid, as described by Aitken (1985). These grains are then loaded onto greased (silicon grease) stainless steel discs to form a monolayer of a few (~8) milligrams mass and subsequently glowed. The natural TL glow curve produced by quartz consists usually of a combination of peaks at ~325°C and ~375°C. Both peaks are sufficiently stable and long-lived at ambient temperatures for Quaternary dating applications, whereas TL peaks are too short-lived below ~250°C and are dominated by

black-body radiation above ~450°C. All laboratory operations should be carried out in subdued red light to avoid bleaching by wavelengths.

3.3 Residual thermoluminescence

Residual TL (I_o) is the fraction of natural TL retained by a sample after prolonged exposure to sunlight. It is determined by bleaching a sample for different lengths of time and measuring the remaining TL. The critical question is whether, during the period of sediment transport, bleaching had removed all but the residual fraction by the time of deposition; once deposited, only the surface grains would continue to be bleached. This issue is more important in the dating of Holocene than Pleistocene sediments because the I_o level is a larger proportion of the natural TL in younger material. The I_o level, and the time required to reach it, depends not only on the intensity and spectrum of the bleaching illumination but also on the susceptibility to bleaching of the sample.

Specifically, there are four phenomena that require investigation:

- the bleaching effect of sunlight on the glow peaks used for TL dating
- the similarity of sunlight spectra with those emitted by laboratory sunlamps
- the bleaching efficiency for sediments transported in clear and turbid waters
- the reduction of bleaching caused by the adherence of impurities on the unetched grain surfaces

3.3.1 Sunlight and glow peaks

The 325°C and 375°C glow peaks used for dating quartz respond differently to bleaching (Spooner et al 1988). The 375°C peak is bleached slowly by wavelengths less than 400 nm (ie UV light), resists any bleaching by longer wavelengths and, even after 20 hours exposure to sunlight, may retain 20% of its natural TL. In contrast, the 325°C peak is bleached by all wavelengths up to 700 nm (ie both UV and visible light) and can be bleached fully (ie nil residual TL) in less than one minute. Hence, the 325°C peak is ideal for dating fluvial deposits as it can be rapidly and effectively zeroed even under water which does not transmit UV light (Spooner et al 1988, BW Smith, pers comm, 1989).

3.3.2 Laboratory lamps

Whichever glow peak is used, the relative abundance of the wavelengths present in the solar spectrum should be reproduced faithfully by the sunlamps chosen for laboratory bleaching. The solar spectrum at sea level extends from the infra-red to the near-violet, with maximum intensity in the visible region. In contrast, mercury sunlamps emit a much stronger UV component, which may bleach the 375°C peak to a lower I_o level than is attainable by sunlight (eg Jungner 1988), resulting in an overestimate of the sample age. A better match to the solar spectrum is obtained with xenon discharge lamps and by interposing light filters between the sample and the lamp (Aitken 1985).

3.3.3 Bleaching in water-borne sediments

Xenon lamps and interposed light filters are particularly appropriate for simulating sub-aqueous bleaching conditions: the depth of water through which the light must pass determines the wavelengths available for bleaching, with green and yellow wavelengths transmitted farthest (Berger 1990a). Bleaching of feldspars is possible beneath 7 m of clear water (Kronborg 1983), but conditions are much less favourable in streams heavily laden with suspended washload

(Gemmell 1985) and for quartzes in general (Berger 1988). In the Magela Creek, yellow-brown humic pigments (tannins) derived from vegetation and soils reduce the intensity and wavelengths of sunlight that reach the stream bed (Kirk & Tyler 1986). The blue and UV wavelengths required to bleach the 375°C peak in quartz are strongly absorbed in the upper 1–2 m of flow and the 325°C peak is unlikely to be zeroed by the low intensity of 500–700 nm light that penetrates to the bed.

3.3.4 Surface Impurities

The presence of impurities, such as oxide or organic coatings, on the grain surface will also hinder bleaching by sunlight. Singhvi et al (1986) found that >70% of the natural TL remained in oxide-coated quartz grains after being bleached for ~17 hours, whereas that had first been etched (to remove surface coatings). If the grains were already stained prior to being transported, then the I_0 level obtained in the laboratory after etching will be lower than that attained in antiquity and, therefore, the age of the sample will be overestimated. If the staining is post-depositional then the correct I_0 level will be obtained, in the absence of other bleaching problems.

3.4 Bleaching

For each sample, knowledge of the physics of bleaching must be combined with geomorphological judgement to decide its probable degree and duration of exposure to sunlight prior to burial. The efficacy of bleaching depends on the transporting agency involved, be it (in order of decreasing likelihood of complete zeroing) wind, water, glaciers or mass movements. Equally important is the environment of deposition, as bleaching is apt to be ineffective in water that is deep or opaque (Berger 1990a, Forman 1990) and along streams that are heavily shaded. Exposure to sunlight is also influenced by the timing of transport, with minimal bleaching during events of short duration and none at night. Furthermore, the opportunity for bleaching is related to the grain-size of a sample via its likely mode of transportation: silt will be suspended higher in the fluid medium and travel further prior to deposition than sand (eg loess in air or washload in water).

In the Magela Creek catchment, the I_0 level may be influenced by post-depositional processes. The aforementioned development of oxide coatings is not problematic, but the residual TL level could be lowered after burial by bushfires or termite activity. Mound-building termites excavate buried sediments, exposing them to sunlight on the exterior of their mounds and, again later, during erosion of unoccupied mounds. This repeated exposure to sunlight provides a much greater opportunity for complete bleaching than might otherwise be afforded by the brief exposure received during sediment transport. By the time of final burial, therefore, sediments derived from termite mounds may have reached the I_0 level reproduced later in the laboratory. Bushfires can reach ground surface temperatures of 500°C, which is sufficient to erase completely the TL signal of the surface grains. Laboratory bleaching would yield an erroneously high I_0 level for these grains and their date of deposition would be underestimated. However, if the sediment was already well-bleached prior to the bushfire then the error in the laboratory-determined I_0 level would be small and a reliable age would be obtained.

The combined result of these environmental influences during and after transportation precludes an unambiguous estimation of the I_0 level of a buried sample from physical principles alone. An alternative means of estimating this quantity is to determine the residual TL level attained by surficial sediments emplaced under similar geomorphological conditions at, or near, the sample site. It is imperative that the surface and buried samples were transported by the same process and were deposited in similar environments. As the depositional processes operating at any particular site may have changed through time, a suitable surface sample may have to be found away from the original site. The two sites should have similar mineral assemblages and

environmental dose rates and, ideally, several surface samples should be analysed to define the characteristic I_o level. For wind-blown deposits in which each grain is well-bleached by sunlight, the I_o level of deeply buried samples is equivalent to the natural TL level remaining in the surface monolayer of grains (Gardner et al 1987, Lu et al 1987, Readhead 1988). In contrast, grains on the surface of water-lain deposits may be bleached more completely than those comprising the bulk of the deposit. This would occur, for example, in lakes that experience brief bursts of sedimentation followed by periods of quiescence during which only the surface monolayer would continue to be bleached. Similarly, in ephemeral stream channels such as the Magela Creek, grains exposed on the stream bed surface during periods of no flow are bleached to a greater extent than is achieved during sub-aqueous transport. For such deposits, a more representative I_o level is obtained from immediately beneath the surface monolayer or from within the most recent sedimentation unit (eg the core of a dune).

3.5 Equivalent dose

The age of a sample is determined not only from its natural TL and residual TL levels, but also from the conversion rate of radiation dose to TL (Relation I). The latter is evaluated experimentally from portions that are irradiated, at $>10^7$ times the environmental dose rate, by a calibrated β or γ radiation source. As dose-rate effects have been noted for quartz (Aitken 1985, McKeever 1985), TL ages should be independently verified with, say, ^{14}C ages. The short-term loss of TL after laboratory irradiation (termed 'anomalous fading' by Wintle, 1973) should also be investigated, although this phenomenon is mostly restricted to feldspars. These problems aside, the laboratory dose required to generate an amount of TL equal to that produced in antiquity (the natural TL) is termed the 'equivalent dose' or ED. This can be determined in a number of ways, of which the 'regenerative', 'additive-dose' and 'partial-bleach' methods are most often employed (Wintle & Huntley 1982, Aitken 1985, Berger 1988). No one method has received universal acclaim, with each possessing certain advantages and disadvantages, as discussed shortly.

The ED is calculated for glow curve temperatures in the range 260–500°C, which includes those TL peaks suitable for dating Quaternary quartz. If the TL has accumulated without leakage during antiquity, then the ED will be consistent over this temperature range and the sample is said to have passed the 'plateau test' (Aitken 1985). The mean value across the ED plateau (ED_n) is used to determine the sample age:

$$\text{Age} = \frac{ED_n}{\text{dose rate}} \qquad \text{(Relation II)}$$

where ED_n represents the radiation dose accumulated by the sample since its last exposure to sunlight

However, this equation will overestimate the age of a sample if it was bleached in the laboratory to a lower I_o level than that attained in antiquity. This problem is restricted to the regenerative and additive-dose methods which, unlike the partial-bleach approach, make assumptions regarding the residual TL at time-zero. It is circumvented by using the ED of a surface or near-surface sample (ED_s) as an analogue for the residual TL in a zero-age deposit (Readhead 1984). The final modified age equation is thus:

$$\text{Age} = \frac{ED_n - ED_s}{\text{dose rate}} \qquad \text{(Relation III)}$$

where ED_n and ED_s are the mean plateau values of the buried and surface (or near-surface) samples respectively

3.5.1 Additive-dose approach

Of the three principal approaches advocated for ED determination, the additive-dose (or 'total-bleach') method is the most widely endorsed. It was developed originally for dating pottery and adapted subsequently for sediments by Singhvi et al (1982). With this method, a portion of the sample is bleached completely (to the I_0 level), another portion is left untreated (to indicate the level of natural TL), and the remainder (still unbleached) is divided into portions that receive a range of artificial doses. The bleached, natural, and irradiated portions are glowed and, for temperature intervals between 300°C and 500°C, the TL intensity is plotted against added dose. These first-glow 'growth curves' are often linear for Holocene quartz but become distinctly sub-linear in older deposits. The latter becomes TL 'saturated' at high doses, typically >200 Gy, and the shape of their growth curves is better described by polynomial (Readhead 1984), saturating exponential (Huntley et al 1988) or saturating-exponential-plus-linear (Berger 1990b) functions. The growth curves are extrapolated between the natural and residual TL levels and the ED is derived from the intercept of the extrapolated curve with the I_0 level (fig 3.1) This method is best suited to feldspar and Holocene quartz, which require only short extrapolations of linear growth curves; second-glows should be performed on young samples to correct for any initial supra-linearity of their first-glow growth curves (Aitken 1985). Uncertainty in the ED intercept is greater with older samples because non-linear growth curves are extrapolated over greater distances between the residual and natural TL levels (Mejdahl 1986).

3.5.2 Regenerative approach

In the regenerative method, most of the sample is subjected to prolonged laboratory bleaching to attain the I_0 level, whilst some of the original material is retained to assess its natural TL. Portions of the fully bleached sample are then artificially irradiated to a series of dose levels. The bleached, bleached and dosed, and natural portions are glowed and the first-glow growth curves are constructed. The ED is obtained from the intercept of the growth curve with the interpolated natural TL level (fig 3.1). This method is suitable for dating old as well as young deposits because there is none of the uncertainty associated with growth curve extrapolations: the shape of the regenerative growth curve is defined over the full range of doses experienced by the sample during burial (ie from the residual to the natural TL levels). It does have the disadvantage that the initial bleaching step may change the sensitivity of the sample to the subsequent irradiation and, hence, the regenerated growth curve may differ from that achieved in antiquity (Rendell & Townsend 1988, Berger 1988). As a check, the growth curve obtained by the additive-dose method should be compared with the regenerated growth curve for the region above the natural TL, and only those samples showing no sensitivity change (ie similar slopes) should be dated (eg Gardner et al 1987, Lu et al 1987, Readhead 1988). Further evidence can be obtained by combining the additive-dose method with a surface (or near-surface) sample to simulate the acquisition of TL during burial (Berger 1988): the resultant growth curves should be of the same form as those of the bleached and regenerated older sample, if the latter has not changed its sensitivity upon bleaching.

3.5.3 'Plateau' and partial-bleach approaches

Both the additive-dose and regenerative methods assume that the sample is bleached to the laboratory-determined I_0 level at the time of burial. For sediments that were only bleached partially before deposition, the ED can be determined using either the 'plateau' additive-dose and regenerative procedures (Mejdahl 1986, 1988) or the 'partial-bleach' approach (Berger 1988).

The 'plateau' procedures are based on the premise that the longest and most stable ED plateau is obtained when a sample is bleached in the laboratory to the exact same level as it attained in antiquity. The additive-dose method is modified insofar as several portions of the sample are

bleached for various exposure times (rather than only one portion being bleached to the I_o level), each of which provide a baseline to intercept with the extrapolated growth curve. The ED is determined from each intercept and the exposure time that produces the 'best' ED plateau is considered to be that which the sample received prior to burial. The 'plateau' regenerative method is more time-consuming: several portions of the sample are bleached for various exposure times and each portion is then artificially irradiated to a series of dose levels, from which growth curves are constructed. The ED is determined for each set of growth curves and the exposure time that yields the 'best' ED plateau is considered to be that which the sample received in antiquity.

The 'partial-bleach' approach (also termed 'R-β' and 'R-γ') deliberately avoids using the I_o level to determine the ED (Wintle & Huntley 1982, Berger 1988). The procedure is to separate the sample into two portions (keeping aside some untreated material to evaluate the natural TL), irradiate both portions to a series of dose levels, and then bleach one portion for a short period of time. The latter must be shorter than the exposure time that the sample received in antiquity, so that only the most easily bleached TL component is drained. Both portions are glowed and the point of intersection between their extrapolated growth curves gives the I_o (fig 3.1). Ideally, several irradiated sets should be bleached for a range of short exposure times and their growth curves constructed: all curves should have a common intersection at I_o, irrespective of bleaching time, provided that none of the latter exceed the original environmental bleach. A drawback of this method is the extrapolation and intersection of two or more growth curves with similar slopes in the case of very short bleach times (Aitken 1985, Mejdahl 1986). For longer bleach times, the angle of intersection is less acute and, hence, less prone to error. However, the possibility arises that these exposures may reduce part of the natural TL present at the time of burial. The uncertainty in ED determination increases with older deposits because their growth curves become markedly non-linear and require extrapolation over large distances; Berger et al (1987) have performed an error analysis of such intersections. Reliable ED determinations have been claimed for Pleistocene feldspars (Berger 1988), but there have been no attempts to apply the partial-bleach method to coarse-grain quartz.

3.5.4 Conclusion

As each method of determining the ED has its strengths and weaknesses, more than one should be applied to each sample. Often the regenerative and additive-dose methods are used in conjunction, as proposed by Readhead (1984): both are based on a laboratory-determined I_o level which necessitates a surface residual TL correction in the sample age calculation (Relation III). In contrast, the 'plateau' and partial-bleach procedures utilize only the most easily bleached fraction of the natural TL and no residual (ie hard-to-bleach) TL correction is required to calculate the sample age (Relation II). The denominator in both age equations is the annual radiation dose supplied to the sample by the decay of radionuclides in the surrounding soil, the penetration by cosmic rays and the internal radioactivity of the sample grains. The importance and variability of each of these components depends on the mineral composition and depositional environment of the sample.

3.6 Dose rate

For most deposits, the radiation flux is derived mainly from the primordial radionuclides ^{238}U, ^{235}U and ^{232}Th (and their decay products) as well as ^{40}K and, to a lesser extent, ^{87}Rb and cosmic rays (Aitken 1985). The α and β particles and γ rays emitted by radioactive decay can travel through rock for distances of ~20 μm, ~2 mm and ~30 cm respectively. In quartz-inclusion dating, only β and γ emissions contribute to the local environmental dose term as the heavily ionized α-irradiated layer of each grain is effectively removed by laboratory etching. The

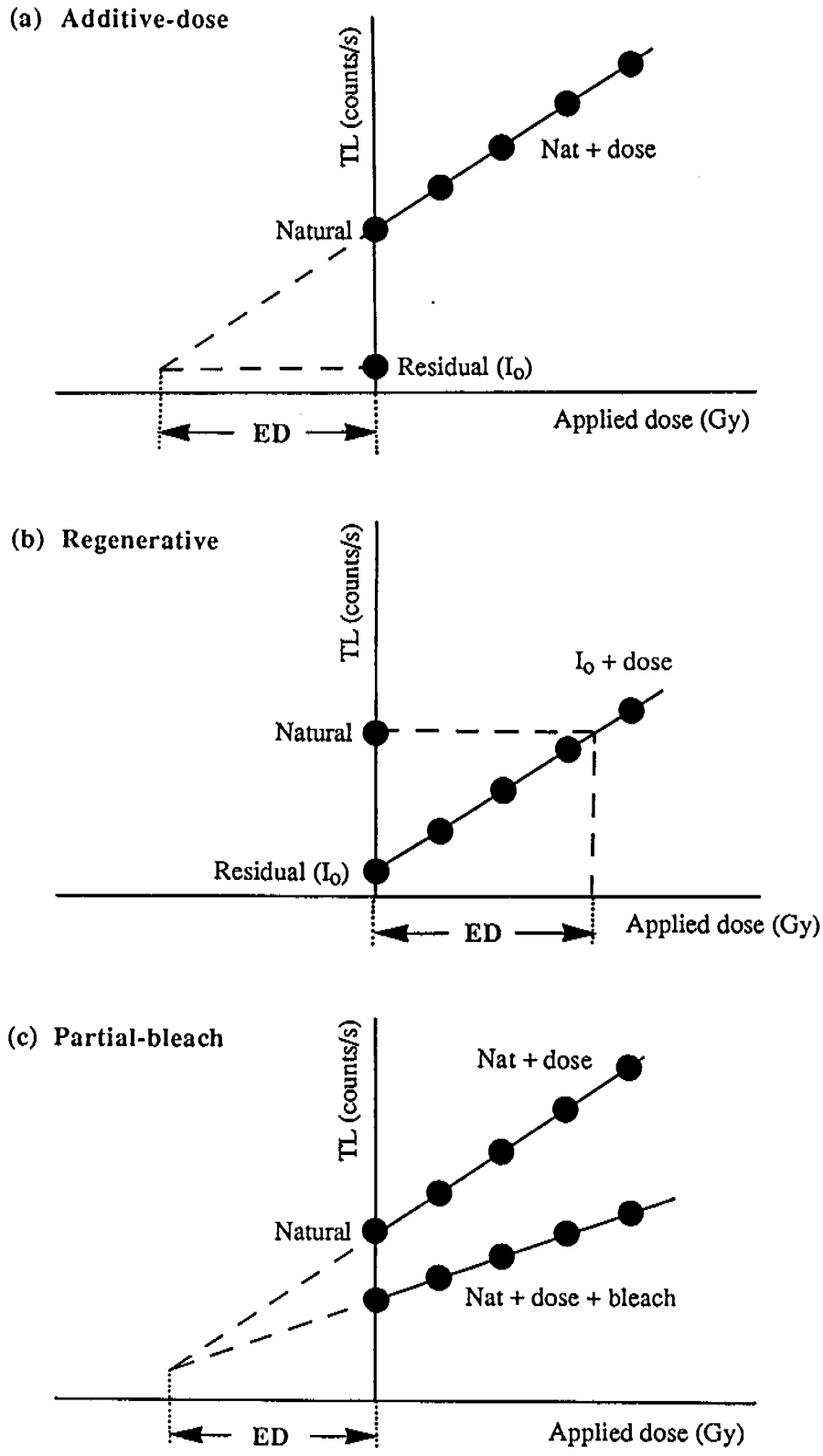

Figure 3.1 Methods of determination of the equivalent dose (ED)

measured β component must be reduced by a factor of 0.90–0.95 because β particles are attenuated slightly in passing through a grain and part of their dose is removed by etching (Mejdahl 1979, Aitken 1985).

The distance travelled by lightly ionizing γ rays demands that a sample is surrounded on all sides by at least 30 cm of homogenous material. Corrections to the γ dose term are required for samples situated close to either the ground surface or intrusive features whose γ dose rate differs from that of the sample (eg bedrock, pedogenic nodules and texture-contrast horizons). Adjustments for proximity to the ground surface are unnecessary if the sample has been buried to a depth of at least 20 cm for two-thirds or more of the burial time (Aitken 1985).

Further corrections are required to the β and γ components of the dose if the sample has not been dry throughout the period of burial. Water absorbs more radiation than sediment, such that in a soil of 30% porosity held at 80% saturation, the annual dose is reduced typically by ~20% (Aitken 1985). Hence, an erroneously young age is obtained for a sample whose moisture content is underestimated. Whilst the soil porosity and present-day moisture content are easily determined, there is always uncertainty about the groundwater history of a site. This uncertainty increases with sample age as there is a greater opportunity for marked climatic changes to have occurred.

Several techniques are available to measure the annual dose derived from the 60 cm diameter sphere of soil surrounding each sample (Aitken 1985, McKeever 1985). These can be split into field and laboratory techniques, although both should be used whenever possible as they each have their strengths and weaknesses.

3.6.1 Field techniques

The most common field method is to bury a sensitive phosphor at the sample site for, say, one year in order to provide a direct measure of the annual dose under present-day soil moisture conditions. This technique is particularly suited to complex stratigraphies because the phosphor integrates the *in situ* dose received by the sample: this includes the γ and cosmic ray components and, with certain methods, also the β dose. Although these phosphors incorporate directly any contemporary disequilibrium in the decay series, there is no means of applying any necessary time-dependent correction. Recently, portable γ-ray spectrometers and scintillometers have been developed to measure the *in situ* γ and cosmic ray flux, as well as determine the individual contributions from uranium, thorium and potassium (Murray 1981, Prescott & Hutton 1988). These apparatus give an accurate dose rate determination in less than an hour and, hence, the variation of dose with burial depth can be measured in a single day. However, secular radioactive equilibrium is assumed, as typically only one nuclide in each decay chain is measured.

'Disequilibrium' prevails in a decay chain when the daughters are in deficiency or in excess with respect to their parents, so that the ratio of their specific activities is not equal to unity. The opposite condition is termed 'secular equilibrium', in which the daughters are 'supported' by their parents and a ratio of unity exists between all nuclide activities along a decay chain. After 6 half-lives, a daughter in disequilibrium usually will have returned (within measurement uncertainties) to a condition of secular equilibrium, in the absence of continued leaching or ingress of radionuclides along the chain; the latter are 'unsupported' by decay of the chain parents. A correction to the dose derived from an unsupported daughter (and subsequent daughters) is required for the period of disequilibrium, but the magnitude of this correction, and the time period affected, depends on the specific nuclide(s) in disequilibrium. It is thus essential to measure the activities of several nuclides in each decay series in order to identify any disequilibrium and make the necessary correction(s). The latter, however, may not be possible for nuclides whose half-life is one sixth or less that of the time period of sample burial, as past episodes of disequilibrium will go undetected if secular equilibrium has since been re-established.

3.6.2 Laboratory techniques

The laboratory techniques used most extensively are thick-source α-counting to measure the uranium and thorium activities (the contribution of each series to the total α count being determined by the 'pairs' technique: Aitken 1985), together with flame emission spectrophotometry, atomic absorption or X-ray fluorescence to determine the potassium content. This approach and that of neutron activation analysis, which can determine the concentration of all three components, provides an integrated estimate of the total dose but assumes secular equilibrium. Even if the latter is true, the α-count rate measured in the laboratory may be greater than that received by the sample whilst buried because gaseous radon isotopes may begin to emanate after the sample is disturbed during collection (Aitken 1985).

In order to deduce the concentrations of individual nuclides in the uranium and thorium decay chains, high-resolution α-particle or γ-ray spectrometry must be used (Aitken 1985). The former technique has the higher resolution but requires time-consuming and specialist chemical separations, whereas sample preparation for γ-ray spectrometry is comparatively simple and rapid (Murray et al 1987). In addition, γ-ray spectrometry can measure the ^{40}K content, but its principal application is in the assessment of disequilibrium in the ^{238}U chain, which most often occurs by migration of ^{226}Ra in groundwaters or by the gaseous diffusion of ^{222}Rn (Tanner 1964, 1978). As most of the dose rate in the uranium chain is derived from the decay of ^{226}Ra to ^{222}Rn and subsequent short-lived daughters, disequilibrium of these two nuclides is especially significant. Their mobility is evaluated from the measured $^{234}Th/^{226}Ra$ and $^{226}Ra/^{210}Pb$ activity ratios respectively. This latter ratio provides a secure estimate of radon loss from the buried sample as ^{210}Pb has a half-life of 22 years and, hence, will take several years to decay significantly following excavation (Murray & Aitken 1988).

In quartz-inclusion dating, the highly ionized α-irradiated outer layer of each grain is mostly (but not entirely) removed by laboratory etching and there is often a trivial dose rate contribution from α particles originating from within each grain (Fleming 1979, Aitken 1985). The combined internal α dose rate is quantified by measuring the activity of a sample before and after etching, either by thick-source α-counting or by fission track mapping: both techniques require only a small number of etched grains. The negligible internal β activity of quartz can be ignored (Mejdahl 1979, Aitken 1985).

Cosmic rays, in particular the penetrating muon component, contribute a small dose to the sample (Aitken 1985). The cosmic ray flux varies with altitude (due to atmospheric absorption), latitude (because the earth's magnetic field gives some shielding near the equator) and depth of burial (due to absorption of electrons in the upper 0.5 m and attenuation of muons in the ground beneath). The latter has the greatest effect, with a typical ground surface dose rate of ~0.28 Gy/kyr decreasing to ~0.15 Gy/kyr at 1 m depth in soils of ~2 kg/m^3 bulk density. The muon flux at depths of 5 m and 10 m is roughly one-half and one-fifth, respectively, of that at 1 m (Prescott & Stephan 1982, Prescott & Hutton 1988).

Methodology

4.1 Sample collection

Samples of quartz sand for TL dating are collected by hand-auger, mechanical auger or from an exposed face such as a stream bank or pit wall. Surface (or near-surface) samples are also taken to determine the characteristic I_o level.

4.1.1 Hand augering

A hand auger is suitable for collecting samples from loose sandy deposits, such as the sand aprons which abut the escarpment of the Arnhem Land plateau. The auger is easily carried to remote sites and can sample effectively to a depth of 10 m. The samples are collected in daylight by rapidly transferring the material in the auger 'bucket' to an opaque bag, having first discarded the outer layer which may become contaminated by the adherence of younger material during auger retrieval. The surface grains of the cleaned sample are exposed only briefly (the bulk of the sample (in the bucket) is not exposed at any stage).

4.1.2 Mechanical augering

Mechanical augering is undertaken with a *Gemco* HP-7 vehicle-mounted drilling rig, using 1.5 m long spiral auger-flights with a diameter of 75 mm; 40 mm of which is suitable for sample retrieval. Collection of TL samples is undertaken at night because it takes 1–2 minutes to clean the contaminants from the auger-flight and a high proportion of the cleaned sample is exposed during this process. Illumination is provided by portable lights covered by a double-layer of *Cinemoid* no. 1 (yellow) filter.

Some mixing of the material trapped on the auger-flight occurs during drilling, especially in hard material. In order to minimise contamination of the TL sample, the lowermost auger is withdrawn and cleaned immediately prior to sampling. Additional material is collected from the 30 cm length of auger-flight above and below the sampling point and used later to determine the environmental dose rate.

4.1.3 Exposed sites

At exposed sections, a PVC pipe of ~5 cm diameter is driven horizontally into the deposit and the entire pipe is then excavated; a smaller (~1 cm) diameter pipe is used for near-surface samples. Only the grains exposed at either end of the pipe are bleached during collection and these are later discarded. For dosimetry purposes, material is also excavated from the sphere of 30 cm radius around each TL sample.

4.1.4 Surface samples

These samples are obtained by lightly brushing the quartz grains resting on the ground surface into a dustpan. This procedure typically collects a surface layer up to three grain diameters (zone of contemporary reworking by raindrop-impacted sheetflow (Moss et al 1979).

4.2 Laboratory procedures

Each TL sample is split into three portions: one portion is used for grain-size, porosity and moisture content determinations, another for radionuclide analyses, and the third portion is kept for equivalent dose determinations. The latter portion is pretreated as follows:

a The surface layer of the sample that was exposed to sunlight during collection is discarded.

b Clay-rich samples are disaggregated using an ultrasonic probe and 4% sodium hexametaphosphate solution.

c Organic matter is oxidised in 30% hydrogen peroxide solution.

d Carbonates are dissolved in 10% hydrochloric acid.

e The 90–125 μm diameter grain-size fraction is separated by mechanical sieving.

f The 90–125 μm fraction is washed (or 'etched') twice in 40% hydrofluoric acid for periods of 5 and 40 minutes to destroy any feldspars and remove the ~10 μm outer coat of each quartz grain.

g Heavy minerals are then separated from the sample using a sodium polytungstate solution of specific gravity 2.74 ± 0.02 g/cm^3.

The final sample consists of 85–115 μm diameter quartz grains that are free from any visible impurities when viewed under a microscope.

All laboratory procedures are conducted in low-intensity yellow light which has been shown experimentally to have a non-detectable bleaching effect for the 375°C quartz peak. This is facilitated by double-wrapping neon tubes in *Cinemoid* no. 1 filter, which transmits light >470 nm. For more sensitive samples a dim red illumination can be achieved using a double-layer of *Lee* 106 'primary red' filter, which transmits only those wavelengths >580 nm (Spooner & Prescott 1986, Smith 1988). Red light is less comfortable for the operator, but reduces the risk of inadvertant sample bleaching in the laboratory (cf Roberts et al 1991).

The treated grains are loaded onto stainless steel discs (10 mm in diameter and 0.5 mm in thickness) that have been smeared with a thin coat of silicone grease. Each disc holds a monolayer of 8.0 ± 0.2 mg of treated quartz, and 30–70 discs are usually prepared for each sample. Laboratory irradiations are conducted with a ^{90}Sr/^{90}Y plaque β source (Oxford laboratory code β [44], Murray & Wintle 1979) that has a nominal activity of 50 mCi and a dose rate of ~5 Gy/minute. The random uncertainty of the calibrated β dose rate is estimated at ± 3% (Murray 1981). An unfiltered *Philips* MLU 300 W sunlamp, placed 25 cm above the sample, is used for bleaching. Samples are also bleached by natural sunlight during the Dry season when the attenuation of the solar UV flux by clouds is at a minimum (Ilyas & Barton 1983, Ilyas 1987).

The loaded discs are heated in a nitrogen atmosphere to 500°C at a rate of 2.5°C/s. The TL signal is detected through *Chance-Pilkington* HA-3 (heat rejecting) and *Corning* 7-59 (blue-violet transmitting) filters with an *EMI* 9635B photomultiplier tube. Photons are counted using *Daybreak* electronics and the resultant glow curve of TL intensity versus temperature is recorded on computer and as a hard copy on a biaxial plotter. All subsequent data analyses are performed using computer programs written by staff of the Alligator Rivers Region Research Institute,

Office of the Supervising Scientist. Examples of data output for a sample reported in Roberts et al (1990, 1991) are shown in Appendix B.

4.3 Equivalent dose determination

The equivalent dose (ED) plateau of each sample is determined using the regenerative method. For young (Holocene) samples, an ED plateau is obtained also by the additive-dose method and the age of deposition is calculated using the mean ED of the two determinations. For older samples, the additive-dose method is used only to check for sensitivity changes in the regenerative method. The 'plateau' and partial-bleach methods may also be applied. The following procedures are the ones used by Roberts et al (1990, 1991).

4.3.1 The regenerative method

a 29 discs are loaded with 8.0 ± 0.2 mg of the pretreated sample. Five discs are kept aside to give the natural TL level and the remainder are bleached for 20 hours. The latter are stored for at least 12 hours before proceeding to the next step.

b The 24 bleached discs are divided into 8 groups of 3 discs, of which one group is kept aside to assess the residual TL level and the remaining sets are each irradiated to different dosages. The maximum dose administered is 5–10 times the expected ED (but never more than 2,000 Gy). Quartz in the Region has been found to TL saturate typically at ~200 Gy, but at doses above ~600 Gy the TL often increases again, presumably due to radiation damage. A typical set of irradiations for a Pleistocene sample (ED ~50 Gy) is 20, 50, 100, 175, 250, 350 and 500 Gy which provides an approximately even spread of points along a saturating exponential curve. For a Holocene sample (ED ~5 Gy) with a linear growth curve, a typical set of doses is 2, 5, 8, 12, 16, 20 and 25 Gy. The irradiated discs are stored for at least 12 hours before proceeding to the next step (following Smith & Prescott 1984).

c Each disc (natural, bleached, and bleached plus irradiated) is glowed twice in order to obtain the total TL signal (on the first heating) and its black-body component (on the second heating). The first-glow and black-body curves are then corrected for temperature shift which may occur during heating because of poor thermal conductivity between the disc and the heating plate, resulting in the glow curve being translated to higher temperatures. For each set of replicates, the glow curves are aligned with the lowest temperature glow curve, which usually involves a shift of The black-body curve is then subtracted from the first-glow curve to give the TL signal which is derived solely from ionizing radiation. At this stage, the glow curves are 'normalised' for both temperature shift and the mass of quartz on each disc.

d The regenerated growth curves of TL intensity versus dose are derived from the normalised glow curves and the mean values from each set of replicates are fitted by linear and saturating exponential least-squares functions. The latter has the general form:

$$L = C_1 [\, 1 - e^{-\lambda(\beta - C_2)} \,] \qquad \text{(Relation IV)}$$

where L is the luminescence in counts per second

C_1 (constant 1) is the TL saturation level in counts per second

C_2 (constant 2) is the intercept on the x-axis in Grays

λ (lambda) is a fitted parameter that describes the degree of curvature

β is the laboratory dose (plus the equivalent dose for the additive-dose method) in Grays

Random uncertainties are computed for each of the three fitted values; error analysis of exponential fits is a topic of current debate (eg Berger et al 1987, Berger & Huntley 1989b, Grun & Macdonald 1989, Poljakov & Hutt 1990).

e The sample ED is computed by linear regression or by iteration of Relation IV, being equal to β when L is coincident with the natural TL level. This calculation is repeated for each 5°C interval between 200°C and 500°C, but on occasions the ED may not be determined using a saturating exponential due to divergence of the fitted parameters. The calculated EDs are plotted against temperature and a 'plateau' sought in the region above 260°C. Those EDs comprising the plateau are averaged and this mean value (ED_n), after deducting the mean plateau value of a modern surface (or near-surface) sample (ED_s), is used to calculate the sample age (Relation III).

f The random uncertainty associated with the ED_n is estimated from four criteria:

- the standard error of the mean plateau value
- the spread of the natural TL replicates at the 325°C or 375°C glow curve peak
- the random uncertainties computed for the best-fit growth curve at 325°C or 375°C
- the scatter obtained from multiple (2-3) ED_n determinations of the same sample

The latter estimate includes an assessment of operator variance. This approach is the most justifiable in a statistical sense and is the best reflection of the true uncertainty of the ED_n (Berger & Huntley 1989a).

4.3.2 The additive-dose method

a 41 discs are loaded with the pretreated sample, of which 5 discs are kept aside to give the natural TL level. The remainder are divided into 12 groups of 3 discs, of which 6 groups are bleached and 6 groups are irradiated. The usual series of bleaching times is 0.5, 1, 2, 5, 10 and 20 hours, but for some samples two additional groups of discs may be bleached for shorter (0.1 and 0.25 hours) or longer (50 and 100 hours) periods. A typical series of doses is 50, 125, 200, 300, 450 and 600 Gy for a buried sample (ED ~50 Gy) and 1, 3, 6, 10, 15 and 20 Gy for a modern surface sample (ED ~1 Gy). A further 5 groups of 3 discs is prepared for the latter sample, and irradiated to 50, 100, 200, 350 and 500 Gy to simulate the acquisition of dose during burial. The bleached and irradiated discs are stored for at least 12 hours before being glowed.

b The temperature normalisation of the glow curves, construction of the first-glow growth curves and calculation of the ED_n (or ED_s) is undertaken as for the regenerative procedure (section 4.3.1 c–f). The only variation lies in selecting the residual TL level attained in antiquity: for quartz bleached completely prior to burial, this should correspond to the TL remaining after a prolonged laboratory bleach. For most samples, the I_o level attained after a 20 hour bleach provides the ED intercept for the extrapolated growth curve.

c For young (Holocene) samples with linear growth curves, the plateau test is applied using both additive-dose and regenerative methods: the mean of their ED_n (or ED_s) values is adopted for purposes of sample age calculation (Relation III) and the random uncertainty incorporates the spread between the pair.

d The additive-dose growth curves are used to check for sensitivity changes in the regenerative growth curves. This comparison is made for buried samples at glow curve temperatures of 325°C, 350°C and 375°C, which includes the two main TL peaks used for dating. At each temperature, the additive-dose points are superimposed on to their corresponding regenerative growth curve, using the regenerative ED (ie the point at which the growth curve intercepts the natural TL level) as the anchor point for the additive-dose naturals (following Readhead 1984). A lack of sensitivity change is evidenced if the additive-dose points lie within the scatter of the regenerative points about their growth curve. This approach is no more subjective than a statistical comparison using the slope of a tangent to non-linear growth

curves because the latter procedure produces large uncertainties for samples close to saturation (Berger 1988).

e The rate of acquisition of dose with time is assumed to be described by first-order kinetics, for which a saturating exponential function is appropriate (Berger 1988). The general applicability of an exponential fit is assessed from its observed goodness-of-fit to modern surface (or near-surface) samples dosed to saturation. These additive-dose growth curves should have the same form as the regenerated growth curves of any underlying samples, provided the TL properties of quartz are similar throughout the deposit.

4.3.3 The 'plateau' methods

The procedures used by the 'plateau' regenerative and additive-dose methods (Mejdahl 1986, 1988) are almost identical to their simpler versions described above.

a For the 'plateau' regenerative method, the first step of the regenerative method (section 4.3.1a is repeated using a shorter bleaching time (0.25 hours) for all 8 groups of 3 discs and the remaining steps are followed identically. If the ED plateau produced by the 0.25 hour bleach is longer and more stable than that produced by the 20 hour exposure, then the sample must not have been bleached completely prior to burial. In this instance, the ED_n computed from the 0.25 hour bleach should be used in the age equation (Relation II) as it better reflects the exposure time that the sample received in antiquity. However, if the sample had been bleached fully prior to burial, then the 20 hour bleach would yield the longest and most stable ED plateau, and the corresponding ED_n should be used to determine the sample age. Ideally, the quality of the ED plateaux should be compared using several additional bleaching times (eg 0.5, 1, 2, and 5 hours) to identify exactly which exposure time produces the 'best' plateau. This would be very time-consuming with the 'plateau' regenerative method, but just such a comparison can be made using the 'plateau' additive-dose method.

b For the 'plateau' additive-dose method, multiple bleaching times are conducted as part of the standard additive-dose procedure (section 4.3.2). Six groups of 3 discs are exposed for 0.5, 1, 2, 5, 10 and 20 hours and, for some samples, two additional groups of discs are bleached for shorter (0.1 and 0.25 hours) or longer (50 and 100 hours) periods. The 'total-bleach' additive-dose method subsequently uses only the 20 hour bleach to calculate the ED (section 4.3.2b) whereas, with the 'plateau' method, each different exposure time provides a baseline to intercept with the extrapolated growth curve. As a result, ED intercepts and the corresponding ED plateaux are obtained for up to 8 different bleach times: the 'best' plateau corresponds to the true exposure time received by the sample in antiquity and should be used to determine its age (using Relation II). This 'plateau' additive-dose procedure is much less time-consuming than the 'plateau' regenerative method because extra discs are needed only to provide the residual TL baselines and not to construct the growth curves.

4.3.4 The partial-bleach method

The partial-bleach approach (Berger 1988) involves the following steps:

a 50 discs are loaded with the pretreated sample and divided into 5 groups of 10 discs. Each group is divided into 5 sets of 2 discs, which are treated in the same manner as the additive-dose samples (section 4.3.2): four pairs of discs are irradiated to different dosages (typically 50, 100, 200 and 300 Gy for a sample with an ED ~30 Gy) and one pair remains as natural. These discs are stored for at least 12 hours before proceeding to the next step.

b Thus far, all 5 groups are identical. Four groups are then bleached for different exposure times (typically 1 minute, 10 minutes, 2 hours and 20 hours) and the remaining group is not

bleached; the latter is equivalent to the additive-dose procedure. Table 4.1 outlines the treatment of the five groups.

The bleaching times chosen should include at least two that are shorter in duration than the bleach received by the sample in antiquity. All discs are stored for at least 12 hours before being glowed.

c The temperature normalisation of the glow curves and construction of the first-glow growth curves is performed by repeating steps c–d of the regenerative procedure (section 4.3.1). The ED is computed, at each 5°C interval between 200°C and 500°C, from the intercept of the Group A growth curve with the growth curve of each other Group (table 4.1). If the sample was bleached completely in antiquity, then the ED given by all the groups will be identical. Alternatively, if the sample was bleached for, say, one hour prior to burial, then the correct ED will be obtained only from the intercept of the Group A growth curve with the growth curves of Groups B and C: these latter two should intersect the Group A growth curve at the same point to yield an identical ED. The equivalent doses obtained from Groups D and E will be erroneously large because, at these extended laboratory exposure times, more TL is bleached from the sample than was achieved in antiquity. As the correct bleaching time is not known in advance, it is preferable to have at least two growth curves that agree on the point of intersection (Berger 1988). These ED intercepts are plotted against temperature and the ED_n is computed by the procedures described previously. As this method involves only the most light-sensitive TL component, the sample age is calculated (from Relation II) without deducting the ED of a modern surface sample.

Table 4.1 Typical treatment of loaded discs, prior to glowing, for the partial-bleach method (natural TL + β dose + bleach time)

Group A	Group B	Group C	Group D	Group E
N + 0 Gy + 0 min	N + 0 Gy + 1 min	N + 0 Gy + 10 min	N + 0 Gy + 2 hrs	N + 0 Gy + 20 hrs
N + 50 Gy + 0 min	N + 50 Gy + 1 min	N + 50 Gy + 10 min	N + 50 Gy + 2 hrs	N + 50 Gy + 20 hrs
N + 100 Gy + 0 min	N + 100 Gy + 1 min	N + 100 Gy + 10 min	N + 100 Gy + 2 hrs	N + 100 Gy + 20 hrs
N + 200 Gy + 0 min	N + 200 Gy + 1 min	N + 200 Gy + 10 min	N + 200 Gy + 2 hrs	N + 200 Gy + 20 hrs
N + 300 Gy + 0 min	N + 300 Gy + 1 min	N + 300 Gy + 10 min	N + 300 Gy + 2 hrs	N + 300 Gy + 20 hrs

4.4 Anomalous fading

'Anomalous fading' is the depletion of the TL signal immediately following laboratory irradiation (Wintle 1973). The stored TL decays logarithmically with time and is anomalous because this instability is not expected from kinetic considerations. Quartz is not prone to such short-term fading (Aitken 1985) but exceptions have been reported (Readhead 1988). It is thus considered prudent to check for fading in selected samples. The following procedure is employed:

a 18 discs are loaded with the pretreated sample, of which half are heated to 500°C, in order to drain their natural TL signal. These discs are stored for at least 12 hours before proceeding to the next step.

b The two groups of 9 discs (termed 'drained' and 'undrained') are divided into 3 sets of 3 discs. One set of discs from each group is irradiated (typically to ~50 Gy) and then stored for at least one year before being glowed.

c 13 days prior to this glowing, a second set of 3 discs from each group is irradiated to the same dosage and, just 12 hours before glowing, the third set of discs from each group is similarly irradiated. All 18 discs are glowed on the same day.

d By this stage, the 9 'undrained' discs have been glowed only once whereas the 9 'drained' discs have been glowed twice: this provides an opportunity to examine the first-glow and second-glow behaviour of the 325°C and 375°C peaks. The first-glow ('undrained') set of discs are used to characterise the magnitude of anomalous fading in unheated quartz. The second-glow ('drained') group are used to indicate whether the fading behaviour is different for samples heated in antiquity by, say, a high-temperature bushfire. For both groups, the magnitude of fading is quantified by comparing the TL intensity of the discs stored for only 12 hours with those stored for longer periods; the TL intensity is measured at the 325°C and 375°C glow peaks.

4.5 Environmental dose rate

The environmental dose rate, which forms the denominator in the age equation (section 3.1), is deduced from the specific activities of radionuclides in the uranium and thorium decay chains, as well as ^{40}K, measured by high-resolution γ-ray spectrometry. Methods of sample preparation and analysis are discussed in detail by Murray et al (1987) and only a summary description follows. Of the material collected from within the sphere of 30 cm radius around a TL sample, about 250 g is ground to a fine powder and cast in a polyester resin. After a delay of at least 23 days (6 half-lives of ^{222}Rn), the cast is placed on an n-type intrinsic germanium detector (relative efficiency ~20%) and an energy spectrum is obtained for the γ-emitting nuclides in the sample.

In the ^{238}U decay series, the γ-emitting nuclides of greatest interest are ^{234}Th, ^{226}Ra and ^{210}Pb. The parent ^{238}U activity is estimated from its daughter, ^{234}Th, between which secular equilibrium generally prevails in sediments (Murray et al 1987). As neither of the subsequent daughters, ^{234}U and ^{230}Th, are strong γ emitters, their activities are estimated from the weighted mean of the ^{234}Th and ^{226}Ra determinations, assuming secular equilibrium. Although the ^{235}U chain contributes only a small fraction of the total dose to the sample, ^{235}U interferes with the determination of ^{226}Ra. The activity due to ^{235}U is obtained from the ^{234}Th measurement and an assumed $^{235}U/^{238}U$ activity ratio of 0.046 (Murray & Aitken 1988); the remaining activity is ascribed to ^{226}Ra. For samples in which ^{226}Ra is in equilibrium with ^{222}Rn and subsequent daughters, a better estimate of ^{226}Ra activity is provided by the weighted mean of ^{214}Pb and ^{214}Bi. This enables the interference-free ^{235}U activity to be determined and, using the $^{235}U/^{238}U$ activity ratio, the ^{238}U activity to be estimated. The weighted mean of the latter and the measured ^{234}Th activity provides the best estimate of ^{238}U activity, assuming secular equilibrium. The best estimate of ^{222}Rn activity is obtained from ^{226}Ra, provided that gaseous ^{222}Rn (half-life of ~4 days) has not escaped during sample burial: this assumption of secular equilibrium is checked using the ^{210}Pb determination, which provides a measure of the ^{222}Rn retained by the buried sample over the past century (Aitken 1985).

In the ^{232}Th decay series, the parental ^{232}Th activity is determined from its grand-daughter (^{228}Ac) which, for most sediments, is in secular equilibrium with its immediate parent (^{228}Ra) and ^{232}Th (Murray et al 1987). Equilibrium between ^{228}Ac and daughters ^{228}Th and ^{224}Ra is assessed by measurement of the latter. The potential for disequilibrium through gaseous ^{220}Rn escape is much less than in the ^{238}U chain because ^{220}Rn has a half-life of only ~1 minute (Aitken 1985). Unfortunately, its grand-daughter (^{212}Pb) has too short a half-life (~10 hours) to provide an independent check of ^{220}Rn activity whilst the sample was buried. Assuming secular equilibrium, the activities of ^{228}Th and ^{220}Rn are estimated from the weighted mean of the ^{224}Ra, ^{212}Pb and

^{208}Tl measured activities. For samples in which ^{228}Ac is also in secular equilibrium, the ^{232}Th and ^{220}Rn activities are calculated as the weighted mean of the ^{228}Ac and ^{228}Th determinations. Finally, the activity of ^{40}K is measured from its intense and distinct γ emission (Murray & Aitken 1988).

The weighted mean and its weighted error are calculated from the following relations, in which the weights are proportional to the inverse squared errors of the two determinations:

$$\text{mean } X = \frac{X_1/S_1^{\,2} + X_2/S_2^{\,2}}{1/S_1^{\,2} + 1/S_2^{\,2}} \qquad \text{(Relation V)}$$

$$\text{mean } S = \left[\frac{1}{1/S_1^{\,2} + 1/S_2^{\,2}}\right]^{0.5} \qquad \text{(Relation VI)}$$

where mean X and mean S are the weighted mean and weighted error, respectively, for the two determinations $X_1 \pm S_1$ and $X_2 \pm S_2$ (Aitken 1990)

The activities of ^{40}K and the major nuclides in the ^{238}U and ^{232}Th decay chains are multiplied by the conversion factors in table 4.2 to determine their equivalent β and γ dose rates and α count rates.

Table 4.2 Conversion factors used to determine dose rates

Nuclide	Specific activity conversion factors[1]		
	Alpha[2]	Beta[3]	Gamma[3]
^{238}U	0.00973	0.00440	0.00032
^{234}U	0.0124	0.00000	0.00007
^{230}Th	0.0122	0.00005	0.00006
^{226}Ra	0.0125	0.00003	0.00003
^{222}Rn	0.0774	0.00481	0.00800
^{210}Pb	0.0151	0.00211	0.00001
^{232}Th	0.0437	0.00259	0.00470
^{220}Rn	0.0786	0.00451	0.00760
^{40}K	0.0000	0.00263	0.00080

1 Updated by A.S. Murray in 1986 from Murray (1981). Data are for activity concentrations equivalent to 1 Bq/kg of natural uranium in secular equilibrium with its daughters, 1 Bq/kg of ^{232}Th similarly in equilibrium, and 1 Bq/kg of ^{40}K.

2 Conversion of Bq/kg to counts/ks, assuming the count rate is taken on a ZnS screen of 42 mm diameter, with a threshold set to reject 15% of counts from a thick-source of ^{232}Th with all daughters in secular equilibrium. Relation VII is used to convert counts/ks to mGy/yr.

3 Conversion of Bq/kg to mGy/yr.

4.6 Internal dose rate

The α count rates are converted to dose rates by the following relation:

$$D_\alpha = 1.28\, a\, \alpha \qquad \text{(Relation VII)}$$

where D_α is the α dose rate in mGy/year

a is the relative efficiency of α particles at producing TL when compared with β particles and γ rays (estimated as 0.10 ± 0.05)

α is the count rate in counts/ks of the etched sample (Aitken, 1985).

The α dose rate is not deduced directly by thick-source α-counting because of the potential for 'overcounting' (Murray 1982, Wintle & Dijkmans 1988, Zoller & Pernicka 1989). Instead, the α count rate of the etched sample is computed as the product of the radionuclide activities of the unetched sample (measured by γ-ray spectrometry), the conversion factors listed in table 4.2, and the ratio of α counts before and after the sample is etched. Only the latter step requires thick-source α-counting, but any errors associated with it or the assumed a value are not critical as the internal α activity of etched quartz contributes only a few percent to the total dose rate. The count rates determined for the individual nuclides are then summed over the uranium and thorium decay series and inserted into Relation VII (as the α term).

The α count rate is taken on a ZnS scintillation screen of 42 mm diameter using *Daybreak* equipment, with a threshold set to reject 15% of counts from a thick-source of ^{232}Th with all daughters in secular equilibrium. Etched grains of 80-115 μm diameter and unetched grains of 90–125 μm diameter are oven dried, spread evenly over the screen to ~2 mm depth, and counted unsealed until at least 200 counts are recorded. This typically requires ~3 days counting for the etched extracts and screen blanks. The count rate for the etched grains (minus the background level) is divided by the count rate for the unetched grains (minus the background level) to give the etched/unetched α count ratio. It may not be possible to determine this ratio for all samples because of the general paucity of etched material, however any errors are trivial in terms of the total dose rate.

4.7 Soil moisture content

The β and γ dose rates calculated for the individual nuclides in the uranium and thorium decay chains, and for ^{40}K, are summed and the total β dose rate is reduced by a factor of 0.93 ± 0.03. The latter corrects for the intra-granular attenuation of β particles and the removal by etching of the β-irradiated coat from each grain (Mejdahl 1979). The dose rates are then corrected for β and γ absorption by groundwater using the equations proposed by Zimmerman (1971) and recommended by Aitken and Xie (1990):

$$\beta_{wet} = \frac{\beta dry}{1 + (1.25 \times W \times L)} \qquad \text{(Relation VIII)}$$

$$\gamma_{wet} = \frac{\gamma dry}{1 + (1.14 \times W \times L)} \qquad \text{(Relation IX)}$$

where β_{dry} and γ_{dry} are the β and γ dose rates determined from the dry sample

W is the saturated water content of the sample (expressed as the ratio of weight of water to dry weight of sample)

L is the average level of saturation maintained by the sample over its period of burial (expressed as a fraction of the saturated water content)

β_{wet} and γ_{wet} are the reduced β and γ dose rates for the wet sample

As γ rays can travel ~30 cm through soil, the moisture content of the soil surrounding the sample must also be considered in Relation IX. The α dose rate originates from within the quartz grains, so does not require adjustment for the inter-granular moisture content.

Samples are selected from a range of depositional environments and their saturated water contents (a function of their porosities) is measured in the laboratory. For each type of deposit, an estimate is made of the fraction of time spent in a fully saturated, 50% saturated and totally dry state (table 4.3). These estimates are based on field observations of the soil moisture content during augering and excavation. At most sites, the contrast between the moisture regimes of

present-day Wet and Dry seasons is probably as great as any fluctuations that have occurred in the late Pleistocene due to climatic changes. Consequently, the uncertainties assigned to the soil moisture estimates embrace not only modern seasonal variations but probably also any hydrologic changes that have occurred throughout the period of sample burial.

The estimated soil moisture content is kept constant for all samples at any one site, and thus is included as a systematic uncertainty in the sample age determinations. Consequently, only the random uncertainty should be used to compare TL ages at a site, whereas the total (random plus systematic) uncertainty should be used to compare TL ages between sites or with ^{14}C ages.

Table 4.3 Moisture contents of TL dated deposits in the Alligator Rivers Region (from Roberts et al 1991)

Depositional environment	Number of months per year spent at			Mean
	100% sat.	50% sat.	0% sat.	% sat.[1]
Sand apron				
head	2	1	9	20 ± 20
toe	2	2	8	25 ± 20
Floodplain				
abandoned	3	2	7	35 ± 20
active	3	3	6	40 ± 20
Ephemeral lake				
margin	4	4	4	50 ± 25
centre	8	2	2	75 ± 25
Magela Creek (Holocene trench)	7	4	1	75 ± 25

1 Mean ± random uncertainty. The mean is based on field observations of soil moisture content during sample collection and, therefore, reflects present-day moisture conditions. The error term is estimated to accommodate not only contemporary Wet-Dry seasonal variations but also the probable range of variation due to long-term climatic change.

4.8 Cosmic ray dose rate

The cosmic ray dose rate is assumed to be 0.28 ± 0.05 mGy/yr for surface (and near-surface) samples and 0.15 ± 0.025 mGy/yr for buried samples (Prescott & Stephan 1982, Aitken 1985, Prescott & Hutton 1988). The latter is a suitable estimate for samples located within 3 m of the ground surface at sites that have undergone steady sedimentation (eg sand aprons). For samples buried deeper, the uncertainty of the cosmic ray dose rate is trivial in comparison with the uncertainties associated with the groundwater history at a site. In these older deposits, there has been a greater length of time available not only for the soil moisture content to have fluctuated but also for radionuclides (eg isotopes of radium and radon) to have migrated.

4.9 Age calculation program

The α, β, γ and cosmic ray dose rates are summed to give the total dose rate received by the sample: this value is used to determine the sample age (from either Relation II or Relation III). The full computational procedure for the age determination and the propagation of uncertainties is detailed in the computer program listed in Appendix A. This program allows the dose rate to be corrected for disequilibrium due to excess ^{226}Ra (and daughters) by calculating separately the dose rate derived from the supported and the unsupported ^{226}Ra. Such disequilibrium has been reported for modern (Johnston et al 1987) and ancient (Nanson et al 1990) fluvial sediments in the

Magela Creek catchment. Input and output files for two hypothetical samples are included in Appendix A. Sample #1 exhibits an excess of ^{226}Ra over ^{230}Th, whereas the uranium chain is in secular equilibrium in Sample #2. It should be noted that the final age estimate has a total uncertainty that is calculated as the arithmetic sum of the random and systematic uncertainties. This approach yields a larger total uncertainty than adding the random and systematic terms in quadrature, as advocated by Aitken (1985).

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Appendix A

Age calculation program with input and output files for two hypothetical samples

```
      FTN7X,L,S
      $FILES(0,4)
      PROGRAM TLDOSE
C     **
C     **
C     **
C     Modified version supplied by Andrew Murray; copied from HP 25/4/90.
      COMMON/DDATA/DCON,ALCON
      COMMON/CALC/ALPHA,BETA,GAMMA,ACT
C     C
      REAL DCON(10,2),ALCON(10),ACT(10,2),ALPHA(10,2), BETA(10,2)
      REAL GAMMA(10,2)
      REAL ACOUNT(4),ARCOUNT(4),BDOSE(4),BRDOSE(4),GDOSE(4),GRDOSE(4)
      REAL SDOSE(4),USDOSE(4),AGE(4)
      CHARACTER*3 YE,BL,SUPPORT,NO,ALPHAWC
      CHARACTER*8 LABEL(10)
      CHARACTER*25 CONTROL,BLANK,OUTPUT,GDATA,DODAT,ALDAT,NAME
      INTEGER CNTRL,OUDAT,AIN,DIN
C
      DATA YE/'YES'/BL/'  '/NO/'NO '/
      DATA LABEL/'U-238  ','U-234  ','Th-230 ','Ra-226 ','Rn-222 '
     :    ,'Pb-210 ','Th-232 ','Rn-220 ','K-40  ','    '/
      DATA BLANK/'          '/
      DATA GDATA/'/TL/TLOUT'/
      DATA DODAT/'/TL/DODAT'/
      DATA ALDAT/'/TL/ALDAT'/
      DATA COSMIC/0.15/ECOSMIC/0.025/
      DATA BATTEN/0.93/EBATTEN/0.03/
      DATA LU/1/
C
      DO 6 I=1,4
      ACOUNT(I)=1E-20
      ARCOUNT(I)=1E-20
      BDOSE(I)=1E-20
      BRDOSE(I)=1E-20
      GDOSE(I)=1E-20
      GRDOSE(I)=1E-20
6     CONTINUE
      lu=loglu(i)
C
C     Set up control file .....
```

```
C
      WRITE(lu,'(" Give control file name [TERM] _")')
      READ(lu,10) CONTROL
10    FORMAT(A25)
      IF(CONTROL.EQ.BLANK) THEN
      CNTRL=LU
      ELSE
      OPEN(UNIT=24,FILE=CONTROL)
      CNTRL=24
      ENDIF
C
C     What is name of output file?
5     FORMAT(" Give name of output file [TLOUT::PHYSICS] _")
      READ(CNTRL,10)OUTPUT
      IF(OUTPUT.EQ.BLANK) OUTPUT=GDATA
      OPEN(UNIT=40,FILE=OUTPUT)
      OUDAT=40
C
C     What is the sample name?
      IF(CONTROL.EQ.BLANK) WRITE(lu,'(" Give name of sample _")')
      READ(CNTRL,'(A25)') NAME
      WRITE(40,'(//,"Dose Rate Data for Sample ",A25,///,
     :      "Group analyses, (dry weight)")') NAME

      OPEN(UNIT=26,FILE=DODAT)
      DIN=26
      OPEN(UNIT=28,FILE=ALDAT)
      AIN=28
      CALL CONV_READ(DIN,AIN)
C     DCON now contains conversion data from Bq/kg to beta and gamma Gy/ka
C     ALCON now contains conversion data from Bq/kg to alpha counts/ks
C
C     Now read activity data into ACT
      IF(CONTROL.EQ.BLANK)WRITE(lu,'(" Give radionuclide activities in"
     :      ,"Bq/kg",/," ")')
      DO 12 I=1,9
      IF (CONTROL.EQ.BLANK) WRITE(lu,10)LABEL(I)
      READ(CNTRL,*) ACT(I,1),ACT(I,2)
12    CONTINUE
      WRITE(40,'(//" Nuclide  Activity  Alpha  Beta"
     :    "  Gamma ",/,
     :    " Bq/kg  count/ks  Gy/ka"
     :    "  Gy/ka ",/," ")')
C
C     Convert activity data into dose rate data and put in BETA and GAMMA
C     Convert activity data into predicted alpha count rate and put into
C     ALPHA
      CALL ABGCALC
      DO 13 I=1,6
      WRITE(40,100) LABEL(I),ACT(I,1),ALPHA(I,1),BETA(I,1),GAMMA(I,1)
13    CONTINUE
      WRITE(40,'(" ")')
      DO 14 I=7,8
```

```
      WRITE(40,100) LABEL(I),ACT(I,1),ALPHA(I,1),BETA(I,1),GAMMA(I,1)
14    CONTINUE
      WRITE(40,'(" ")')
      WRITE(40,100) LABEL(9),ACT(9,1),ALPHA(9,1),BETA(9,1),GAMMA(9,1)
100   FORMAT(A11,3X,F8.1,6X,F9.3,5X,2(F9.4,5X))
C     If any Th-230/Ra-226 disequilibrium is externally supported, set
C     FLAG=0, if not supported, and age needs to be calculated iteratively,
C     set Flag=1.
      IF(CONTROL.EQ.BLANK) WRITE(lu,'(" Is Th-230/Ra-226 ratio",
     :  " supported? [YES] _")')
      READ(CNTRL,30) SUPPORT
      IF(SUPPORT.EQ.YE.OR.SUPPORT.EQ.BL) THEN
      FLAG=0
      ELSE
      FLAG=1
      ENDIF
30    FORMAT(A3)
C     Calculate total dose rates and total predicted alpha count rate,
C     as appropriate for value of FLAG
      CALL ABGSUM(FLAG,GDOSE,GRDOSE,BDOSE,BRDOSE,ACOUNT,ARCOUNT)
C     Now read water content,fractn of sat. & calc. w.c. correctn factors
      IF(CONTROL.EQ.BLANK)WRITE(lu,'(" Saturated water content (%), ",
     :     "and abs. error _")')
      READ(CNTRL,*) SATWC,ESATWC
      IF(CONTROL.EQ.BLANK)WRITE(lu,'(" Fraction of above during burial,
     :     and abs. error _")')
      READ(CNTRL,*) FWC,EFWC
C
      IF(CONTROL.EQ.BLANK)WRITE(lu,'(" Is alpha dose subject to water",
     :     " content effects?[NO] _")')
      READ(CNTRL,30) ALPHAWC
      IF(ALPHAWC.EQ.NO.OR.ALPHAWC.EQ.BL)THEN
      FAWC=1
      ELSE
      FAWC=0
      ENDIF
C
      DELTA=SATWC*FWC/100
      EDELTA=(SQRT((ESATWC/SATWC)**2+(EFWC/FWC)**2))*DELTA
C     EDELTA is the abs. error on the fractional buried w.c. DELTA
C     EDELTA is external systematic (3)
      GWC=1/(1+DELTA*1.14)
      EGWC=-1/(1+(DELTA+EDELTA)*1.14)+GWC
      EGWC=((1/(1+(DELTA-EDELTA)*1.14)-GWC)+EGWC)/2
C     GWC is correction factor for gamma dose rate due to w.c., EGWC is
C     ext. syst. abs. error in GWC.
C     Above is approximation, because errors are not symmetric
      BWC=1/(1+DELTA*1.25)
      EBWC=-1/(1+(DELTA+EDELTA)*1.25)+BWC
      EBWC=((1/(1+(DELTA-EDELTA)*1.25)-BWC)+EBWC)/2
C     BWC is correction factor for beta dose rate due to w.c., EBWC is
C     ext. syst. abs. error in BWC.
C     Above is approximation, because errors are not symmetric
```

Input file for sample #2

output2			:output file name	
#2 (secular equilibrium)			:sample name	
13.0	2.0		U-238	radionuclide
13.0	2.0		U-234	analysis of sample
13.0	2.0		Th-230	all activities in Bq/kg
13.0	0.5		Ra-226	all errors abs.
13.0	4.0		Rn-222	
13.0	4.0		Pb-210	
25.0	0.5		Th-232	
25.0	0.5		Rn-220	
40.0	3.0		K-40	
YES			is Th-230/Ra-226 ratio supported?	
20.0	5.0		saturated water content (%), and abs. error	
0.25	0.05		fract. of saturation during burial, abs. error	
NO			Is alpha dose rate subject to w.c. effects?	
0.05	0.02		etch/total alpha count ratio, and abs. error	
0.10	0.05		'a' value and abs. error	
10.0	1.0	0.3	ED, abs. rand. error, abs. syst. error.	

File used as control file for calculation of TL dose rates and ages, using /TL/TLDOSE
This file input2

```
      BRDOSE(3)=BRDOSE(3)*BRDOSE(1)
      BRDOSE(2)=BRDOSE(2)*BATTEN
      BRDOSE(4)=BRDOSE(4)*BATTEN
      EARAT=EARAT*ARAT
      WRITE(40,200) ARAT,EARAT
200   FORMAT(/"Alpha count ratio",11X,F5.3," +/-",F5.3)
      WRITE(40,300) (ACOUNT(I),BDOSE(I),GDOSE(I), I=1,4)
300   FORMAT(/"Terrestrial dose rates in dry soil"//
     :   "Supported comp. (Gy/ka)  ",1X,3(F9.4,5X),/,
     :   " uncertainties (rand)  ",1X,3(F9.4,5X),/,
     :   "      (ext syst) ",1X,3(F9.4,5X),/,
     :   "      (int syst) ",1X,3(F9.4,5X))
      IF(FLAG.NE.0) THEN
      WRITE(40,400) (ARCOUNT(I),BRDOSE(I),GRDOSE(I),I=1,4)
      ENDIF
400   FORMAT(/"Unsupported comp. (Gy/ka) ",1X,3(F9.4,5X),/,
     :   " uncertainties (rand)  ",1X,3(F9.4,5X),/,
     :   "    (ext syst) ",1X,3(F9.4,5X),/,
     :   "    (int syst) ",1X,3(F9.4,5X))
C     Write out calculated water correction factors. Errors are ext syst (3).
      WRITE(40,500) SATWC,ESATWC,FWC,EFWC
500   FORMAT(/'Sat. water content, (%)',7X,F4.1,' +/-',F4.1,/
     :   'Fract. of sat. while buried',4X,F5.3,' +/-',F5.3)
      IF(FAWC.GE.1) THEN
      AWC=0
      EAWC=0
      ENDIF
      WRITE(40,600) AWC,BWC,GWC,EAWC,EBWC,EGWC
600   FORMAT(/"Calc. w.c. correct. factors",1X,3(F9.4,5X),/
     :   " uncertainties (ext syst)",1X,3(F9.4,5X))
C     Now perform water content corrections (on alpha dose, only if FAWC=0)
      CALL WCCOR(GDOSE,GRDOSE,GWC,EGWC)
      CALL WCCOR(BDOSE,BRDOSE,BWC,EBWC)
      IF(FAWC.LE.0) THEN
      CALL WCCOR(ACOUNT,ARCOUNT,AWC,EAWC)
      ENDIF
C     Add cosmic to stable component of gamma dose rate only
C     ECOSMIC is ext. systematic. (3)
      GDOSE(1)=GDOSE(1)+COSMIC
      GDOSE(3)=SQRT(GDOSE(3)**2+ECOSMIC**2)
C     ACOUNT, BDOSE and GDOSE now contain the final alpha, beta and gamma/
C     cosmic components of the dose rate. Stable components of dose rate
C     should now be summed, as should unstable. For supported Th-230/Ra-226
C     this is the average burial dose rate. Random errors (2) are added in
C     quadrature, ext. syst. errors (3) and int. syst. errors (4) are added
C     linearly. Finally, random and int syst are combined in quadrature,
C     to give overall random error.
C
      SDOSE(1)=ACOUNT(1)+BDOSE(1)+GDOSE(1)
      SDOSE(2)=SQRT(ACOUNT(2)**2+BDOSE(2)**2+
     :    GDOSE(2)**2)
      SDOSE(3)=ACOUNT(3)+BDOSE(3)+GDOSE(3)
      SDOSE(4)=ACOUNT(4)+BDOSE(4)+GDOSE(4)
```

```
      SDOSE(2)=SQRT(SDOSE(2)**2+SDOSE(4)**2)
C
      USDOSE(1)=ARCOUNT(1)+BRDOSE(1)+GRDOSE(1)
      USDOSE(2)=SQRT(ARCOUNT(2)**2+
     :    BRDOSE(2)**2+
     :    GRDOSE(2)**2)
      USDOSE(3)=ARCOUNT(3)+BRDOSE(3)+GRDOSE(3)
      USDOSE(4)=ARCOUNT(4)+BRDOSE(4)+GRDOSE(4)
      USDOSE(2)=SQRT(USDOSE(2)**2+USDOSE(4)**2)
C     Write out results of present day dose rate calculation
      WRITE(OUDAT,50) SDOSE(1),SDOSE(2),SDOSE(3)
      IF(FLAG.NE.0) WRITE(OUDAT,60) USDOSE(1),USDOSE(2),USDOSE(3)
      IF(FLAG.EQ.0) USDOSE(1)=0
50    FORMAT(//"Total Dose Rate (Gy/ka)",//,
     :   "Supported Component",9X,F9.5," +/-",F9.5," (rand)",
     :   F9.5," (syst)")
60    FORMAT(/ "Unsupported Component",7X,F9.5," +/-",F9.5," (rand)",
     :   F9.5," (syst)")
C
C     Now read ED, and random and systematics abs. errors
C
      IF(CONTROL.EQ.BLANK) WRITE(lu,'("ED, abs. rand. error, abs.",
     :      "syst. error")')
      READ(CNTRL,*)ED,EEDR,EEDS
      IF(ED.LE.0) GOTO 55
      WRITE(40,65)ED,EEDR,EEDS
65    FORMAT(//,"Equivalent Dose (Gy)",10X,F7.3,"  +/-",F7.3,
     :   " (rand) ",F7.3," (syst)")
C
      CALL CALCAGE(ED,EEDR,EEDS,SDOSE,USDOSE,AGE)
      AGE(3)=AGE(2)+AGE(3)
      WRITE(40,70) (AGE(I),I=1,3)
70    FORMAT(//,"Age is ",F6.2,"ka, +/-",F6.2," (rand)",F6.2,
     :   " (total)")
C
55    WRITE(40,700) A,EA
700   FORMAT(//"Note: 1/ a value assumed to be",F4.2," +/-"F4.2)
      WRITE(40,800) BATTEN,EBATTEN
800   FORMAT( "   2/ beta attenuation taken as",F4.2," +/-"F4.2)
      WRITE(40,900) COSMIC,ECOSMIC
900   FORMAT( "   3/ cosmic contribution",F5.3," +/-"F5.3' Gy/ka")
      IF(FLAG.NE.0) WRITE(40,1000)
1000  FORMAT("   4/ Radon escape from unsupported component is"/
     :    "   assumed to be the same as from the supported.")
      END
C
C
C
C
C

      SUBROUTINE CONV_READ(DIN,AIN)
C     Reads in dose rate and alpha count rate conversion data
      COMMON/DDATA/DCON,ALCON
```

```
      REAL DCON(10,2),ALCON(10)
      INTEGER DIN,AIN
      DO 10 I=1,10
      READ(DIN,*) DCON(I,1),DCON(I,2)
      READ(AIN,*) ALCON(I)
10    CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE ABGCALC
C     Calculates beta and gamma dose rates and alpha count rates for each
C     group, and stores results with errors in BETA, GAMMA and ALPHA
      COMMON/CALC/ALPHA,BETA,GAMMA,ACT
      COMMON/DDATA/DCON,ALCON
      REAL DCON(10,2),ALCON(10),ACT(10,2),ALPHA(10,2), BETA(10,2)
      REAL GAMMA(10,2)
C
      DO 10 I=1,10
      ALPHA(I,1)=ACT(I,1)*ALCON(I)
      ALPHA(I,2)=ACT(I,2)*ALCON(I)
      BETA(I,1)=ACT(I,1)*DCON(I,1)
      BETA(I,2)=ACT(I,2)*DCON(I,1)
      GAMMA(I,1)=ACT(I,1)*DCON(I,2)
      GAMMA(I,2)=ACT(I,2)*DCON(I,2)
10    CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE ABGSUM(FLAG,GDOSE,GRDOSE,BDOSE,BRDOSE,ACOUNT,ARCOUNT)
C     Sums doses and count rates into stable and unstable alpha, beta
C     and gamma components. Errors are int. syst., and so load into (4)
      COMMON/CALC/ALPHA,BETA,GAMMA,ACT
C
      REAL ACT(10,2),ALPHA(10,2), BETA(10,2),GAMMA(10,2)
      REAL RALPHA(10,2),RBETA(10,2),RGAMMA(10,2)
      REAL ACOUNT(4),ARCOUNT(4),BDOSE(4),BRDOSE(4),GDOSE(4),GRDOSE(4)
C
C     If FLAG=0 treat as stable only, else separate into supported and
C     unsupported Ra-226 and daughters, and sum separately.
10    CONTINUE
      IF (FLAG.LE.0) THEN
      DO 11 I = 1,10
      ACOUNT(1)=ACOUNT(1)+ALPHA(I,1)
      ACOUNT(4)=SQRT(ACOUNT(4)**2+ALPHA(I,2)**2)
      BDOSE(1)=BDOSE(1)+BETA(I,1)
```

```
      BDOSE(4)=SQRT(BDOSE(4)**2+BETA(I,2)**2)
      GDOSE(1)=GDOSE(1)+GAMMA(I,1)
      GDOSE(4)=SQRT(GDOSE(4)**2+GAMMA(I,2)**2)
11    CONTINUE
      ELSE
      RAFRACT=ACT(3,1)/ACT(4,1)
C     If Ra-226 is less than Th-230, it is presumed growing in, if greater
C     than Th-230, it is presumed decaying towards equilibrium
      ERAFRACT=SQRT((ACT(3,2)/ACT(3,1))**2+(ACT(4,2)/ACT(4,1))**2)
      ERAFRACT=ERAFRACT*RAFRACT
      RAFRACT=1-RAFRACT
C     RAFRACT is the fraction of the total Ra-226 activity that is unsupported
C     by Th-230 if >0, or the missing amount, expressed as a fraction of
C     present Ra-226, if C  Now need to sum the two components, supported and unsupported.
C     We do not consider the >1 option further (assumed stable, FLAG=0)
C
      IF(RAFRACT.LE.0) THEN
      FLAG=0
      GOTO 10
      ENDIF
C
      DO 13 I=4,6
      RALPHA(I,1)=ALPHA(I,1)*RAFRACT
      RALPHA(I,2)=SQRT((ALPHA(I,2)/ALPHA(I,1))**2
     :    +(ERAFRACT/RAFRACT)**2)*RALPHA(I,1)
      ALPHA(I,1)=ALPHA(I,1)-RALPHA(I,1)
      ALPHA(I,2)=SQRT(ALPHA(I,2)**2+(ERAFRACT*ALPHA(I,1))**2)
C     Simplification here when I=4, i.e. Ra-226. Error has been folded
C     twice, once in calc. of ERAFRACT, once here. This line should be
C     corrected for I=4 only. Similarly below.
      RBETA(I,1)=BETA(I,1)*RAFRACT
      RBETA(I,2)=SQRT((BETA(I,2)/BETA(I,1))**2
     :    +(ERAFRACT/RAFRACT)**2)*RBETA(I,1)
      BETA(I,1)=BETA(I,1)-RBETA(I,1)
      BETA(I,2)=SQRT(BETA(I,2)**2+(ERAFRACT*BETA(I,1))**2)
      RGAMMA(I,1)=GAMMA(I,1)*RAFRACT
      RGAMMA(I,2)=SQRT((GAMMA(I,2)/GAMMA(I,1))**2
     :    +(ERAFRACT/RAFRACT)**2)*RGAMMA(I,1)
      GAMMA(I,1)=GAMMA(I,1)-RGAMMA(I,1)
      GAMMA(I,2)=SQRT(GAMMA(I,2)**2+(ERAFRACT*GAMMA(I,1))**2)
13    CONTINUE
C     ALPHA, BETA and GAMMA contain only supported fractions. Now sum
      DO 16 I = 1,10
      ACOUNT(1)=ACOUNT(1)+ALPHA(I,1)
      ACOUNT(4)=SQRT(ACOUNT(4)**2+ALPHA(I,2)**2)
      BDOSE(1)=BDOSE(1)+BETA(I,1)
      BDOSE(4)=SQRT(BDOSE(4)**2+BETA(I,2)**2)
      GDOSE(1)=GDOSE(1)+GAMMA(I,1)
      GDOSE(4)=SQRT(GDOSE(4)**2+GAMMA(I,2)**2)
16    CONTINUE
C     RALPHA, RBETA and RGAMMA contain only unsupported fractions. Now sum
      DO 17 I = 4,6
      ARCOUNT(1)=ARCOUNT(1)+RALPHA(I,1)
```

```
      ARCOUNT(4)=SQRT(ARCOUNT(4)**2+RALPHA(I,2)**2)
      BRDOSE(1)=BRDOSE(1)+RBETA(I,1)
      BRDOSE(4)=SQRT(BRDOSE(4)**2+RBETA(I,2)**2)
      GRDOSE(1)=GRDOSE(1)+RGAMMA(I,1)
      GRDOSE(4)=SQRT(GRDOSE(4)**2+RGAMMA(I,2)**2)
17    CONTINUE
      ENDIF
      RETURN
      END
C
C
C
C
C
      SUBROUTINE WCCOR(DOSE,RDOSE,WC,EWC)
C     Corrects dose rates and alpha count rates for the effects of water
C     content. DOSE(2) and EWC are absolute ext syst errors (3).
      REAL DOSE(4),RDOSE(4)
      DOSE(3)=SQRT((DOSE(3)/DOSE(1))**2+(EWC/WC)**2)
      DOSE(1)=DOSE(1)*WC
      DOSE(3)=DOSE(3)*DOSE(1)
      DOSE(2)=DOSE(2)*WC
      DOSE(4)=DOSE(4)*WC
      RDOSE(3)=SQRT((RDOSE(3)/RDOSE(1))**2+(EWC/WC)**2)
      RDOSE(1)=RDOSE(1)*WC
      RDOSE(3)=RDOSE(3)*RDOSE(1)
      RDOSE(2)=RDOSE(2)*WC
      RDOSE(4)=RDOSE(4)*WC
      RETURN
      END
C
C
C
C
C
      SUBROUTINE CALCAGE(ED,EEDR,EEDS,SDOSE,USDOSE,AGE)
C     Calculates age iteratively (in ITER) from
C
C
C     T1 = (ED/DS)-(DU/(LAMBDA*DS))*(EXP(LAMBDA*T2)-1)
C
C     DS is supported dose rate, SDOSE(1), DU is unsupported dose rate,
C     USDOSE(1). LAMBDA is decay constant for Ra-226. T1=T2=age
C
      REAL SDOSE(4),USDOSE(4),AGE(4)
      DUM=0
C     Easy case first
      IF(USDOSE(1).LE.0) THEN
      AGE(1)=ED/SDOSE(1)
      AGE(2)=SQRT((EEDR/ED)**2+(SDOSE(2)/SDOSE(1))**2)*AGE(1)
      AGE(3)=SQRT((EEDS/ED)**2+(SDOSE(3)/SDOSE(1))**2)*AGE(1)
      ELSE
C     Now deal with unsupported component. First set up parameters for
```

```
C       calculating AGE(1)
        A=ED
        B=SDOSE(1)
        D=USDOSE(1)
        CALL ITER(AGE(1),A,B,D,DUM)
C       AGE(1) now contains best evaluation of age.
C       Now set up parameters to evaluate random error dependence of age
C       on other parameters. EEDR first.
        A=A+EEDR
        CALL ITER(C1,A,B,D,AGE(1))
        A=ED-EEDR
        IF(A.LE.0) A=1E-20
        CALL ITER(C2,A,B,D,AGE(1))
        C1=(C1+C2)/2
C       C1 now contains absolute error component in AGE(1) arising from
C       random error in ED.
        AGE(2)=C1
        A=ED
        B=SDOSE(1)+SDOSE(2)
        CALL ITER(C1,A,B,D,AGE(1))
        B=SDOSE(1)-SDOSE(2)
        IF(B.LE.0) B=1E-20
        CALL ITER(C2,A,B,D,AGE(1))
        C1=(C1+C2)/2
C       C1 now contains absolute error component in AGE(1) arising from
C       random error in SDOSE(1).
        AGE(2)=SQRT(AGE(2)**2+C1**2)
        B=SDOSE(1)
        D=USDOSE(1)+USDOSE(2)
        CALL ITER(C1,A,B,D,AGE(1))
        D=USDOSE(1)-USDOSE(2)
        IF(D.LE.0) D=1E-20
        CALL ITER(C2,A,B,D,AGE(1))
        C1=(C1+C2)/2
C       C1 now contains absolute error component in AGE(1) arising from
C       random error in USDOSE(1).
        AGE(2)=SQRT(AGE(2)**2+C1**2)
C       Now do same for syst. error. EEDS first.
        A=ED+EEDS
        D=USDOSE(1)
        CALL ITER(C1,A,B,D,AGE(1))
        A=ED-EEDS
        IF(A.LE.0) A=1E-20
        CALL ITER(C2,A,B,D,AGE(1))
        C1=(C1+C2)/2
C       C1 now contains absolute error component in AGE(1) arising from
C       systematic error in ED.
        AGE(3)=C1
        A=ED
        B=SDOSE(1)+SDOSE(3)
        CALL ITER(C1,A,B,D,AGE(1))
        B=SDOSE(1)-SDOSE(3)
        IF(B.LE.0) B=1E-20
```

```
      CALL ITER(C2,A,B,D,AGE(1))
      C1=(C1+C2)/2
C     C1 now contains absolute error component in AGE(1) arising from
C     systematic error in SDOSE(1)
      AGE(3)=SQRT(AGE(3)**2+C1**2)
      B=SDOSE(1)
      D=USDOSE(1)+USDOSE(3)
      CALL ITER(C1,A,B,D,AGE(1))
      D=USDOSE(1)-USDOSE(3)
      IF(D.LE.0) D=1E-20
      CALL ITER(C2,A,B,D,AGE(1))
      C1=(C1+C2)/2
C     C1 now contains absolute error component in AGE(1) arising from
C     systematic error in USDOSE(1)
      AGE(3)=SQRT(AGE(3)**2+C1**2)
C     Now include terms arising from errors in ED
      AGE(2)=SQRT((EEDR/ED)**2+(AGE(2)/AGE(1))**2)*AGE(1)
      AGE(3)=SQRT((EEDS/ED)**2+(AGE(3)/AGE(1))**2)*AGE(1)
      ENDIF
      RETURN
      END
C
C
C
C
C
      SUBROUTINE ITER(C,A,B,D,AGE)
      REAL LAMBDA
C
      LAMBDA=0.433
Ç     Decay constant for Ra-226, (per ka)
      P1=A/B
      P2=D/(LAMBDA*B)
      T1=P1
      DO 20 I=1,100
      T2=P1-P2*(EXP(LAMBDA*T1)-1)
      IF(ABS(T1-T2).LE.1E-04)GOTO 10
      T1=(T2+T1)/2
20    CONTINUE
      WRITE(1,'("ITERATION INCOMPLETE!!!!!!!!!")')
10    CONTINUE
      IF(AGE.LE.0) THEN
      C=T1
      ELSE
      C=ABS(T1-AGE)
      ENDIF
      RETURN
      END
C
C
C
C
C
```

Input file for sample #1

output1			:output file name	
#1 (Ra-226 excess)			:sample name	
13.0	2.0		U-238	radionculide
13.0	2.0		U-234	analysis of sample
13.0	2.0		Th-230	all activities in Bq/kg
20.0	0.5		Ra-226	all errors abs.
19.0	4.0		Rn-222	
19.0	4.0		Pb-210	
25.0	0.5		Th-232	
25.0	0.5		Rn-220	
40.0	3.0		K-40	
NO			is Th-230/Ra-226 ratio supported?	
20.0	5.0		saturated water content (%), and abs. error	
0.25	0.05		fract. of saturation during burial, abs. error	
NO			Is alpha dose rate subject to w.c. effects?	
0.05	0.02		etch/total alpha count ratio, and abs. error	
0.10	0.05		'a' value and abs. error	
10.0	1.0	0.3	ED, abs. rand. error, abs. syst. error.	

File used as control file for calculation of TL dose rates and ages, using /TL/TLDOSE
This file input1

Output file for sample #1

Dose Rate Data for sample #1 (Ra-226 excess)

Group analyses, (dry weight)

Nuclide	Activity	Alpha	Beta	Gamma
	Bq/kg	count/ks	Gy/ka	Gy/ka
U-238	13.0	.126	.0572	.0042
U-234	13.0	.161	.0000	.0009
Th-230	13.0	.159	.0007	.0008
Ra-226	20.0	.250	.0006	.0006
Rn-222	19.0	1.471	.0914	.1520
Pb-210	19.0	.287	.0401	.0002
Th-232	25.0	1.092	.0648	.1175
Rn-220	25.0	1.965	.1127	.1900
K-40	40.0	.000	.1052	.0320
Alpha count ratio		.050 +/- .020		
Terrestrial dose rates in dry soil				
Supported comp.	(Gy/ka)	.0305	.3966	.4447
uncertainties	(rand)	.0122	.0000	.0000
	(ext syst)	.0194	.0128	.0000
	(int syst)	.0021	.0234	.0339
Unsupported comp.	(Gy/ka)	.0045	.0430	.0535
uncertainties	(rand)	.0018	.0000	.0000
	(ext syst)	.0028	.0014	.0000
	(int syst)	.0012	.0116	.0190
Sat. water content, (%)		20.0 +/- 5.0		
Fract. of sat. while buried		.250 +/- .050		
Calc. w.c. correct. factors		.0000	.9412	.9461
uncertainties (ext syst)		.0000	.0177	.0163
Total dose rate (Gy/ka)				
Supported component		.95445 +/-	.05752 (rand)	.05937 (rand)
Unsupported component		.09552 +/-	.03021 (rand)	.00522 (syst)
Equivalent dose (Gy)		10.000 +/-	1.000 (rand)	.300 (syst)

Age is 6.63ka, +/- .90 (rand) 1.18 (total)

Note: 1 a value assumed to be .10 +/- .05
2 beta attenuation taken as .93 +/- .03
3 cosmic contribution .130 +/- .025 Gy/ka
4 Radon escape from unsupported component is assumed to be the same as from the supported.

Input file for sample #2

output2			:output file name	
#2 (secular equilibrium)			:sample name	
13.0	2.0		U-238	radionuclide
13.0	2.0		U-234	analysis of sample
13.0	2.0		Th-230	all activities in Bq/kg
13.0	0.5		Ra-226	all errors abs.
13.0	4.0		Rn-222	
13.0	4.0		Pb-210	
25.0	0.5		Th-232	
25.0	0.5		Rn-220	
40.0	3.0		K-40	
YES			is Th-230/Ra-226 ratio supported?	
20.0	5.0		saturated water content (%), and abs. error	
0.25	0.05		fract. of saturation during burial, abs. error	
NO			Is alpha dose rate subject to w.c. effects?	
0.05	0.02		etch/total alpha count ratio, and abs. error	
0.10	0.05		'a' value and abs. error	
10.0	1.0	0.3	ED, abs. rand. error, abs. syst. error.	

File used as control file for calculation of TL dose rates and ages, using /TL/TLDOSE
This file input2

Output file for sample #2

Dose Rate Data for sample #2 (secular equilibrium)
Group analyses, (dry weight)

Nuclide	Activity	Alpha	Beta	Gamma
	Bq/kg	count/ks	Gy/ka	Gy/ka
U-238	13.0	.126	.0572	.0042
U-234	13.0	.161	.0000	.0009
Th-230	13.0	.159	.0007	.0008
Ra-226	13.0	.163	.0004	.0004
Rn-222	13.0	1.006	.0625	.1040
Pb-210	13.0	.196	.0274	.0001
Th-232	25.0	1.092	.0648	.1175
Rn-220	25.0	1.965	.1127	.1900
K-40	40.0	.000	.1052	.0320
Alpha count ratio		.050 +/- .020		
Terrestrial dose rates in dry soil				
Supported comp.	(Gy/ka)	.0309	.4007	.4499
uncertainties	(rand)	.0124	.0000	.0000
	(ext syst)	.0196	.0129	.0000
	(int syst)	.0020	.0225	.0324
Sat. water content, (%)		20.0 +/- 5.0		
Fract. of sat. while buried		.250 +/- .050		
Calc. w.c. correct. factors		.0000	.9412	.9461
uncertainties (ext syst)		.0000	.0177	.0163
Total dose rate (Gy/ka)				
Supported component		.96369 +/-	.05532 (rand)	.05978 (rand)
Equivalent dose (Gy)		10.000 +/-	1.000 (rand)	.300 (syst)

Age is 10.38ka, +/- 1.20 (rand) 1.91 (total)

Note: 1 a value assumed to be .10 +/- .05
2 beta attenuation taken as .93 +/- .03
3 cosmic contribution .130 +/- .025 Gy/ka

Appendix B

Examples of graphical output for sample KTL164

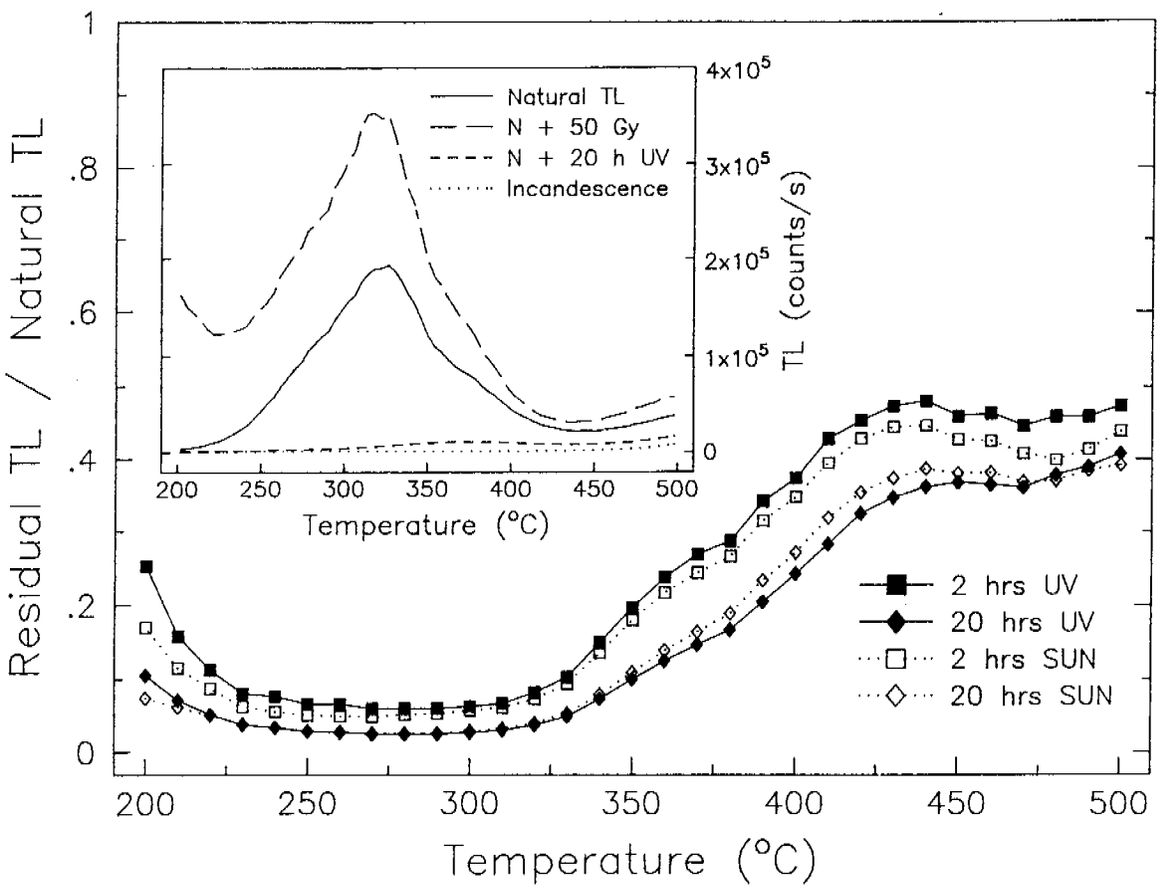

Figure B1 Bleaching curves for sample KTL164 with glow curves inset. This sample is dominated by the 325°C peak with a smaller 375°C component. The 325°C peak is bleached almost entirely after 20 hours of bleaching (by sun or UV lamp), whereas the 375°C peak retains a portion of its original TL even after 20 hours of bleaching.

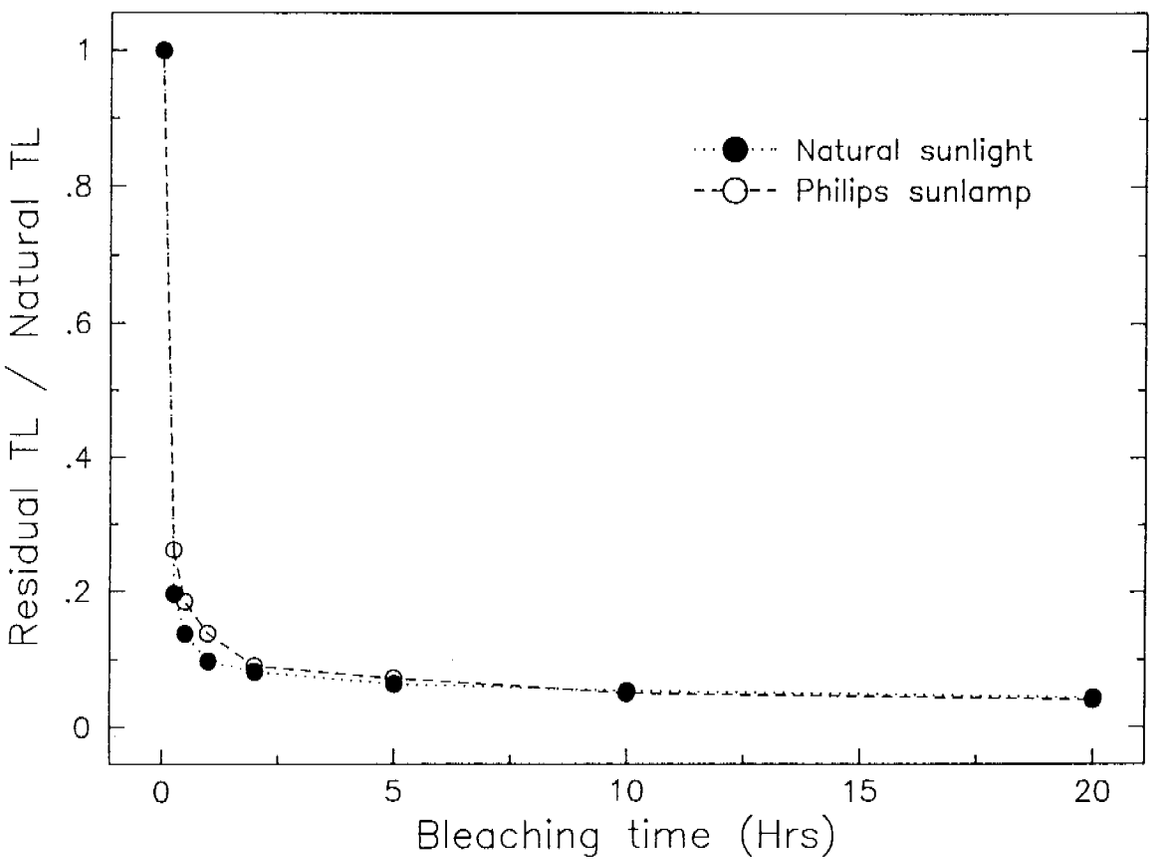

Figure B2 Solar versus UV sunlamp bleaching curves for sample KTL164, at a temperature of 325°C, showing the rapid bleaching to a near residual level by both bleaching methods after only a few hours. However, in the standard regenerative procedure, a bleaching time of 20 hours was used to reach the residual TL level.

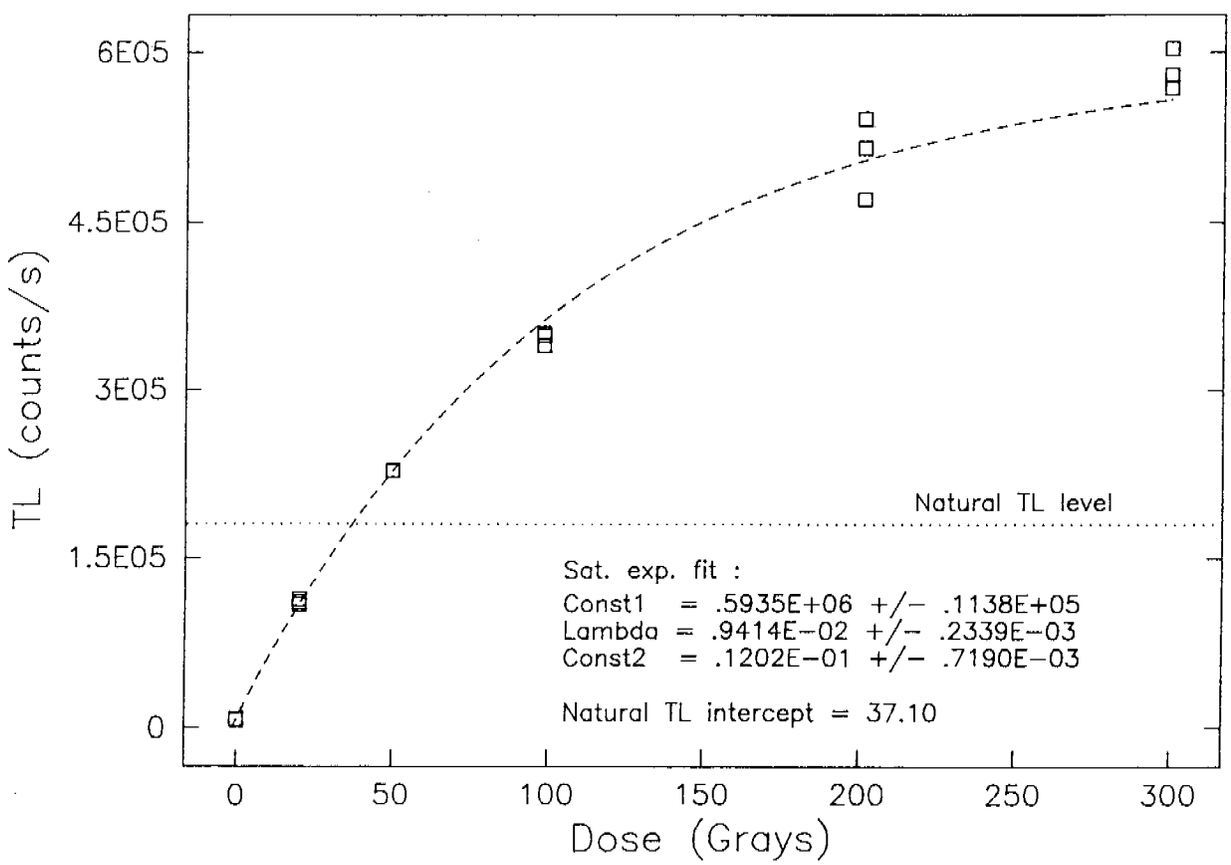

Figure B3 Regenerative first glow growth curve for sample KTL164R, at a temperature of 325°C, fitted by a saturating exponential curve. The regenerated aliquots were bleached initially for 20 hours by a UV sunlamp. The equivalent dose is determined from the intercept of the growth curve with the natural TL level.

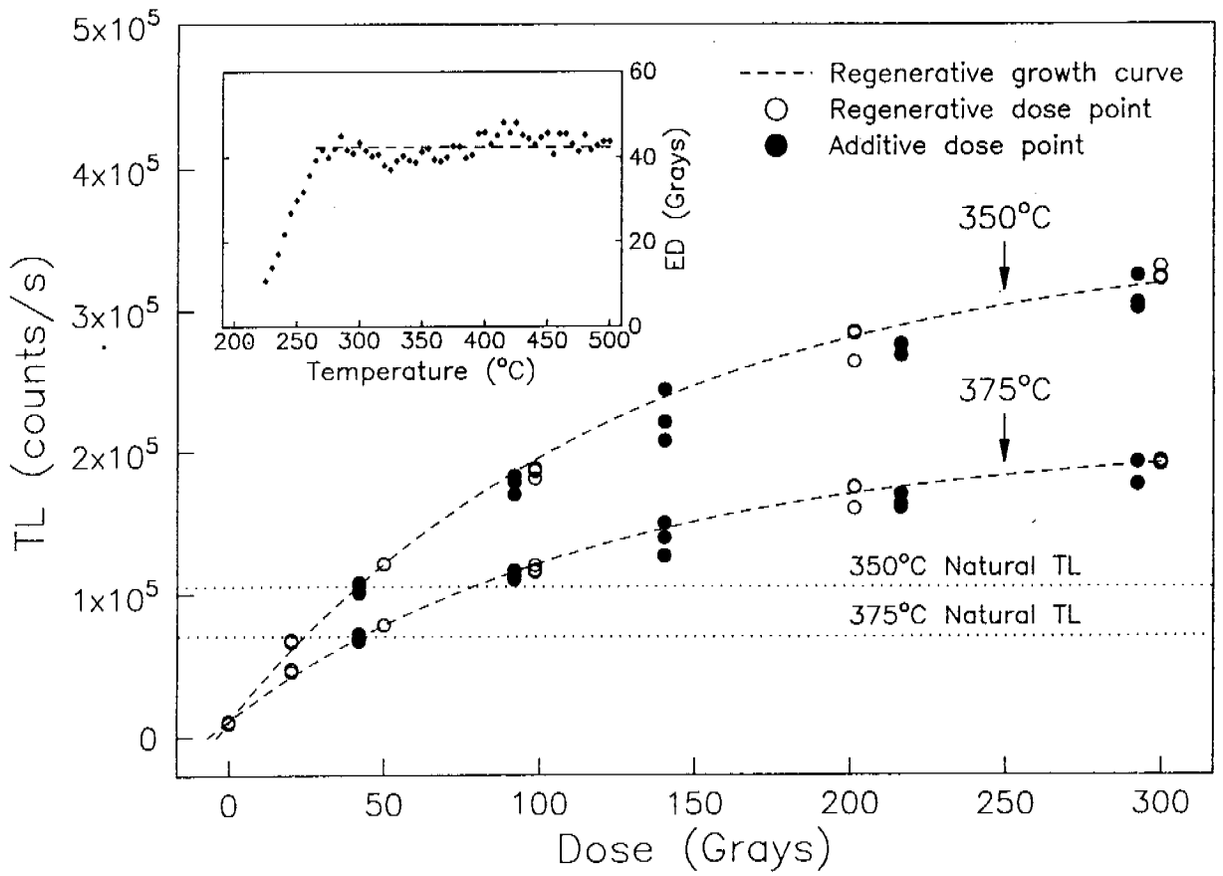

Figure B4 Regenerative growth curves for sample KTL164, at temperatures of 350°C and 375°C. The additive-dose points overlie the regenerative growth curve, which implies that the sensitiveity of the regenerated aliquots has not been affected by their initial 20 hour UV bleach. The inset shows the equivalent dose determined for temperatures between 200°C and 500°C. The sample age is calculated using the mean equivalent dose (42.4 Gy) for the temperature region over which a plateau is observed (265°C-500°C).

Appendix C

Publications arising from the ARRRI thermoluminescence laboratory

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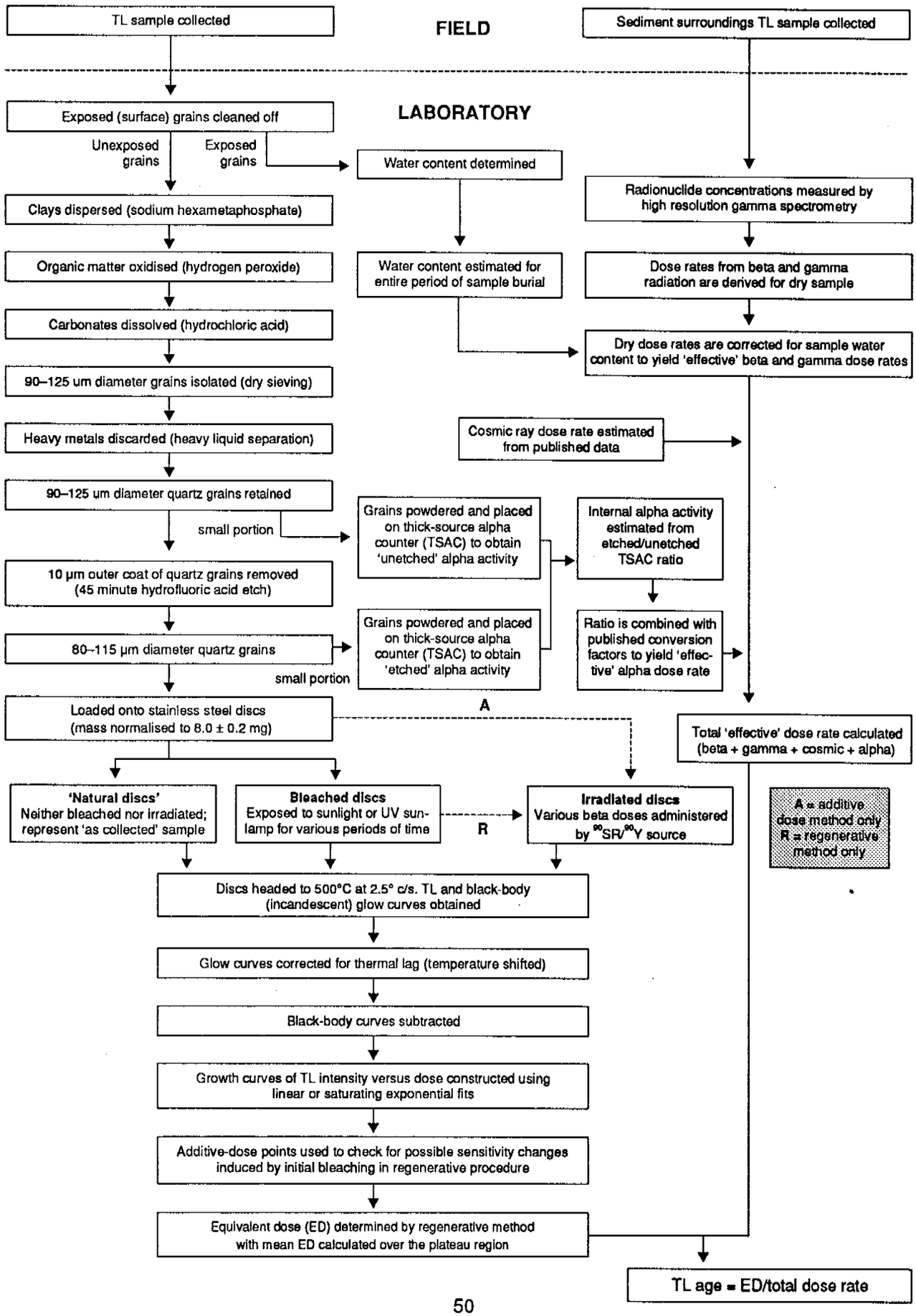
Roberts RG, Nanson GC & East TJ 1991. Sediment budgets and Quaternary history of the Magela Creek catchment, tropical northern Australia. Open file record 80, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

TL dating procedures at the ARRRI



Supervising Scientist for the Alligator Rivers Region

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Alligator Rivers Region Research Institute Research Report 1983
Alligator Rivers Region Research Institute Annual Research Summary 1984-85
Alligator Rivers Region Research Institute Annual Research Summary 1985-86
Alligator Rivers Region Research Institute Annual Research Summary 1986-87
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TM34 Chartres CJ, Walker PH, Willett IR, East TJ, Cull RF, Talsma T & Bond WJ 1991. *Soils and hydrology of Ranger Uranium Mine sites in relation to application of retention pond water.* Technical memorandum 34, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (69pp)

TM35 leGras CAA & Noller BN 1991. *The determination of low concentrations of sodium, potassium, magnesium, calcium and strontium in natural waters by graphite furnace AAS.* Technical memorandum 35, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (18pp)

TM36 Brennan KG, Noller BN, leGras CAA, Morton SR & Dostine PL 1992. *Heavy metals in waterbirds from the Magela Creek flood plain, Alligator Rivers Region, Northern Territory, Australia.* Technical memorandum 36, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (59pp)

TM37 Padovan A 1992. *Isolation and culture of five species of freshwater algae from the Alligator Rivers Region, Northern Territory.* Technical memorandum 37, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (30pp)

TM38 Carter MW, Burns P, & Munslow-Davies L 1993. *Radiotoxicity hazard classification: the basis and development of a new list.* Technical memorandum 38, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (23pp)

TM39 Rippon GD, leGras CAA, Hyne RV & Cusbert PJ 1992. *Toxic effects of cyanide on aquatic animals of the Alligator Rivers Region.* Technical memorandum 39, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (17pp)

TM40 Devonport CC 1992. *A selected GIS bibliography.* Technical memorandum 40, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (91pp)

TM 41 Roberts RG, Uren CJ & Murray AS 1993. *Thermoluminescence dating techniques at the Alligator Rivers Region Research Institute.* Technical memorandum 41, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (63pp)

TM42 GD Rippon & JC Chapman 1993. *Laboratory procedures for assessing effects of chemicals on aquatic animals.* Technical memorandum 42, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra. (26pp)

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