CHAPTER 4

LUMINESCENCE DATING STUDIES

In case of Nal Sarovar core samples, the amount of organic matter in the sediments, below 3m depth was very low (<0.01%). Hence radiocarbon dating of organic matter could be attempted only upto 3m (see Section 3.2.2). The radiocarbon dating of the carbonate nodules at depths of 16m and below gave an age of >38ka, providing a lower age limit for these sediments. The chronology for sediments below 3m was, therefore, obtained using luminescence dating. In this chapter a brief introduction to luminescence dating is provided along with the results of present study.

Luminescence dating is based on the fact that naturally occurring minerals like quartz and feldspars, among others, act as natural dosimeters and preserve a record of dose/irradiation received through time. Decay of natural radionucleides viz. U, Th and K provides a source of constant irradiation. A short exposure to sunlight can, however, erase the geological luminescence to a zero or near zero value. On burial, reacquisition of luminescence begins which is a function of time and hence, is proportional to the age i.e. time since last burial, of the sample. Initially the growth of luminescence is linear but with increasing dose, saturation effect occurs. This puts an upper limit to the dose and hence the age that can be measured using this technique.

The basic advantage of the method accrues from the fact that minerals, being sediment constituents, provide an opportunity to date the sediment itself thereby eliminating any ambiguity of correlation of sample with strata. This is in contrast to the radiocarbon method where organics and carbonates associated with the sediment are dated.

4.1 Thermal and optically stimulated luminescence

The phenomenon of stimulated (optical/thermal) luminescence can be explained using the band theory of solids (Fig. 4.1). The interaction of ionising radiation, α, β and γ (produced by the decay of radioactive nuclides) with crystal results in the production of an avalanche of free electrons and holes. Most of these charges combine instantaneously and release energy either thermally and/or optically. A small fraction of free charges, however, get trapped at various lattice defects in the crystal lattice e.g. vacancies, interstitials etc. The lifetime of these trapped charges varies from 10^{-4} to 10^{9} a. However, thermal or optical stimulation can cause instantaneous detrapping of charges, some of which radiatively recombine with an opposite charge at an appropriate recombination centre. The emitted light is called as Thermally Stimulated Luminescence/Thermoluminescence (TSL/TL) or Optically Stimulated Luminescence (OSL) depending on the type of stimulation. When optical stimulation is done using infra red light, the emitted luminescence is called as Infra Red Stimulated Luminescence (IRSL). Despite the complexity of the process, it turns out that the total number of trapped charges is proportional to the radiation dose and the final luminescence intensity bears a simple proportional relationship to the radiation dose. This forms the basis of application of luminescence phenomena in dosimetry and dating.

4.1.1 Age equation

Given an *ab initio* zero luminescence level, the age equation can be given as

$$\text{Age} = \frac{\text{Total luminescence since last zeroing (L)}}{\text{Luminescence acquisition per year (L/year)}}$$

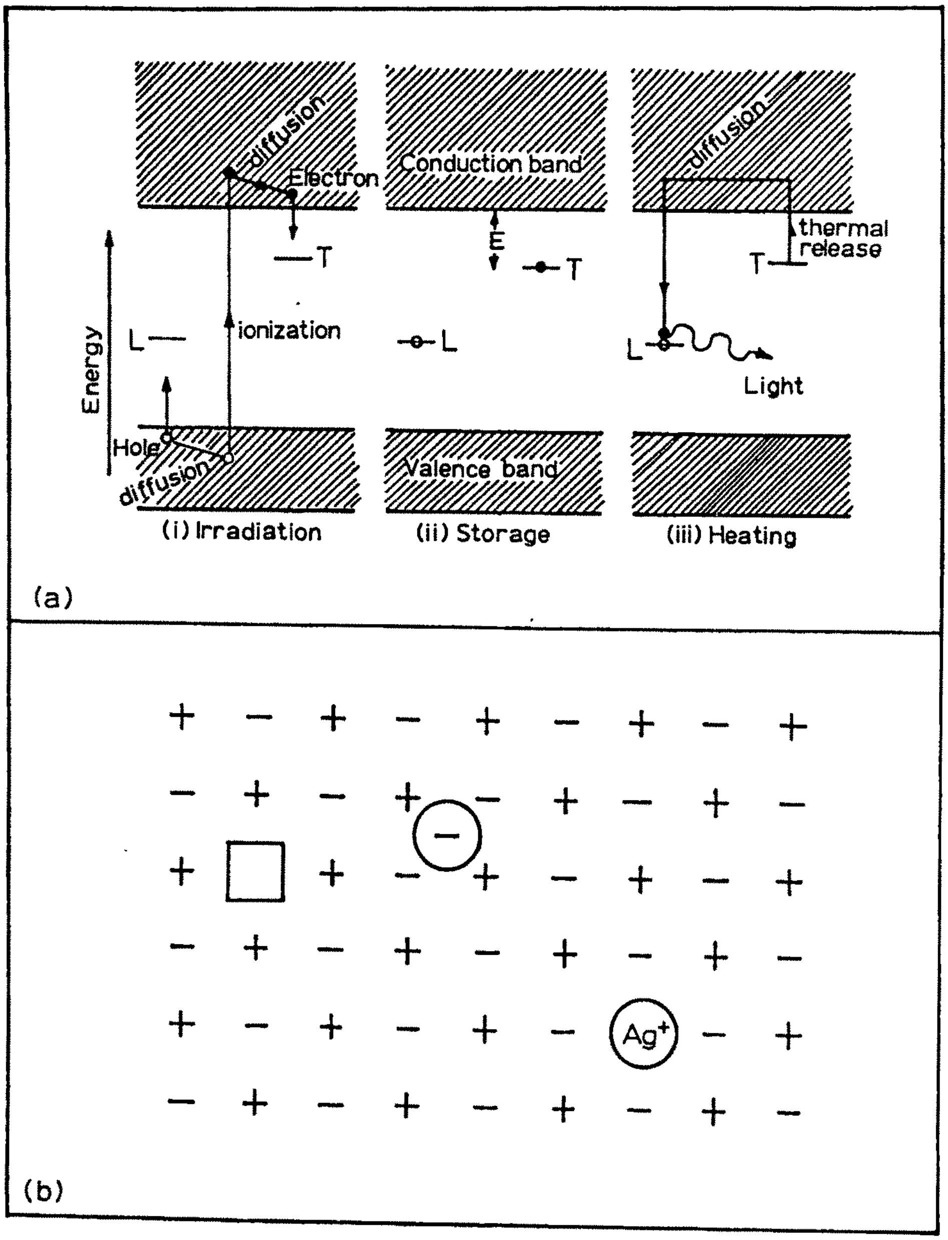

Fig 4.1 (a) Explanation of the basic process of TL induction using the band theory of solids (after Aitken, 1985). (i) Irradiation by ionising radiation results in the production of free charges some of which get trapped at various defects in the crystal. (ii) Energy 'E' is required for the detrapping of the charges. (iii) Stimulation by heating (or optically) can cause detrapping of these charges some of which recombine radiatively with the opposite charge at a recombination centre 'L' and emit light called as TL or OSL depending on the type of stimulation.

(b) Schematic portrayal of simple types of defects such as negative ion vacancy, interstitial defect and impurities in an ionic crystal (after Aitken, 1974) or, $$\text{Age} = \frac{L}{\sum_{\alpha,\beta,\gamma,c} (L/D)*(D/y)} \qquad \text{.....} \quad (4.1)$$

The above equation can be rewritten as,

$$\text{Age} = \frac{L}{\chi_\alpha D_\alpha + \chi_\beta D_\beta + \chi_\gamma D_\gamma + \chi_c D_c} \qquad \text{....}(4.2)$$

The denominator accounts for the summation of the radiation doses from α, β, γ's emitted in the decay of radionucleides and cosmic rays. In the equation, χ_i is the luminescence sensitivity of the sample and is represented as L/unit dose. D_α D_β, D_γ and D_c denote the dose rate due to α, β, γ and cosmic rays respectively. Due to the manner of energy deposition, the high ionisation density and low track length of the alpha particle, the luminescence inducing efficiency of alpha particles is small compared to that of beta or gamma. According to Zimmerman (1971), $\chi_\alpha < \chi_\beta = \chi_\gamma = \chi_c$ and defining the alpha efficiency factor 'a' as,

$$a = \chi_\alpha/\chi_\beta \text{ and } Q = L/\chi_\beta$$

equation 4.2 can now be rewritten as,

$$\text{Age} = \frac{Q}{aD_\alpha + D_\beta + D_\gamma + D_c} \qquad \text{.....}(4.3)$$

where Q is the laboratory β dose that can induce a luminescence level identical to that in the natural sample. It is also known as the equivalent dose (ED). Thus, for the calculation of luminescence age of a sample two parameters have to be measured,

1. The total dose acquired by the sample since the last 'zeroing' event, or its equivalent dose (ED).

2. Dose received per year, i.e. dose rate. This has three components - alpha, beta and gamma which are contributed by U, Th and K in the sample. In addition, the cosmic ray contribution to the dose rate is also considered.

The application of equation 4.3 assumes that there has not been any loss of luminescence with time i.e. that the signal has remained stable.

4.1.2 Luminescence dating of sediments

The luminescence age, as discussed above, gives the time elapsed since the last 'zeroing' event. This event is either the most recent thermal event that caused the sample temperature to rise beyond 500°C or the most recent photo-bleaching event caused due to sun exposure of minerals during weathering and transport. It would seem from Fig. 4.2 that a sun exposure of several hours to several minutes is needed to reduce the TL or OSL respectively, to maximum bleachable level value. This assumption is easily satisfied in case of aeolian sediments which are transported over large distances over long durations. However, in case of sediments transported and deposited by water, there always remains a possibility that bleaching to a residual level may not have been achieved (see Section 4.1.3). In such a case, the unbleached geological luminescence can result in an age overestimation.

Estimation of ED

Estimation of equivalent dose is generally done by constructing a luminescence vs. dose, i.e. the growth curve. The various methods of estimation of ED are briefly discussed below.

1. **Partial bleach method** (Wintle and Huntley, 1980): This method was devised for partially bleached samples. In this method, two growth curves are constructed. For the first, the natural sample is given incremental doses of beta (or gamma) radiation and their TL recorded. For the second, after giving

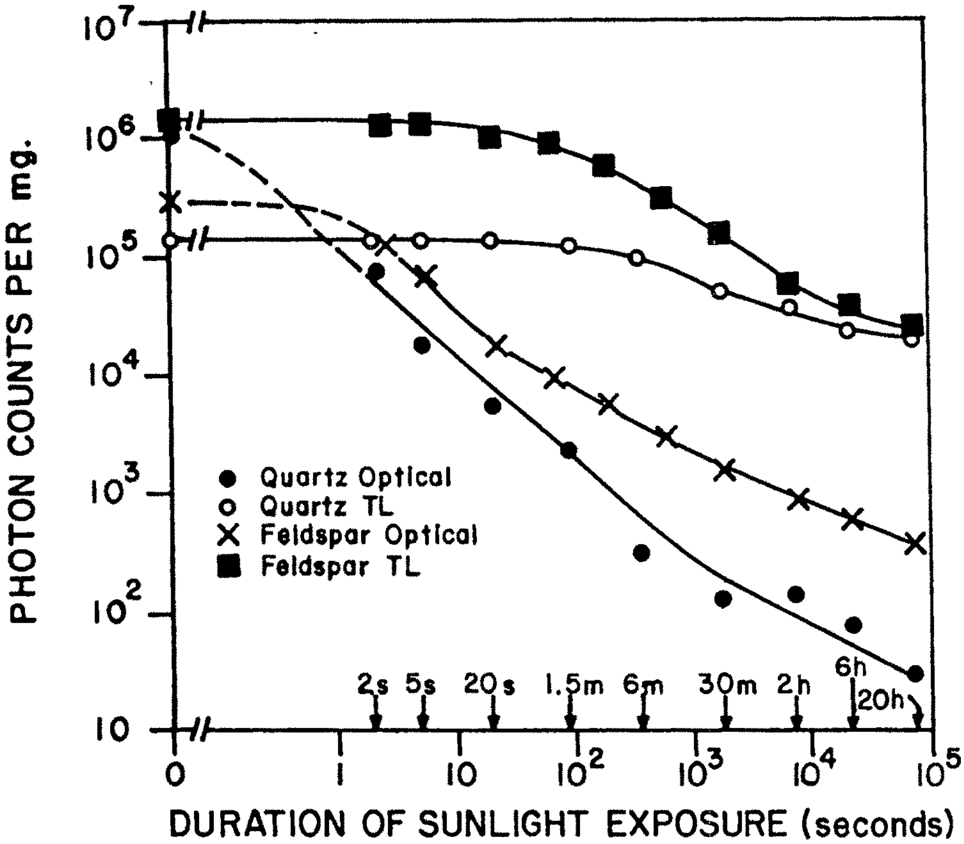

Fig 4.2 Comparative study of bleaching of quartz and feldspar (after Godfrey-Smith et al, 1988) showing faster bleaching of OSL signal; for OSL, 1% of initial signal was reached for quartz after 10 seconds of sun exposure whereas 9 min were required for a feldspar sample. For TL, exposure time of several hours was needed to reduce the signal. Note reverse sensitivity of minerals to bleaching for OSL and TL

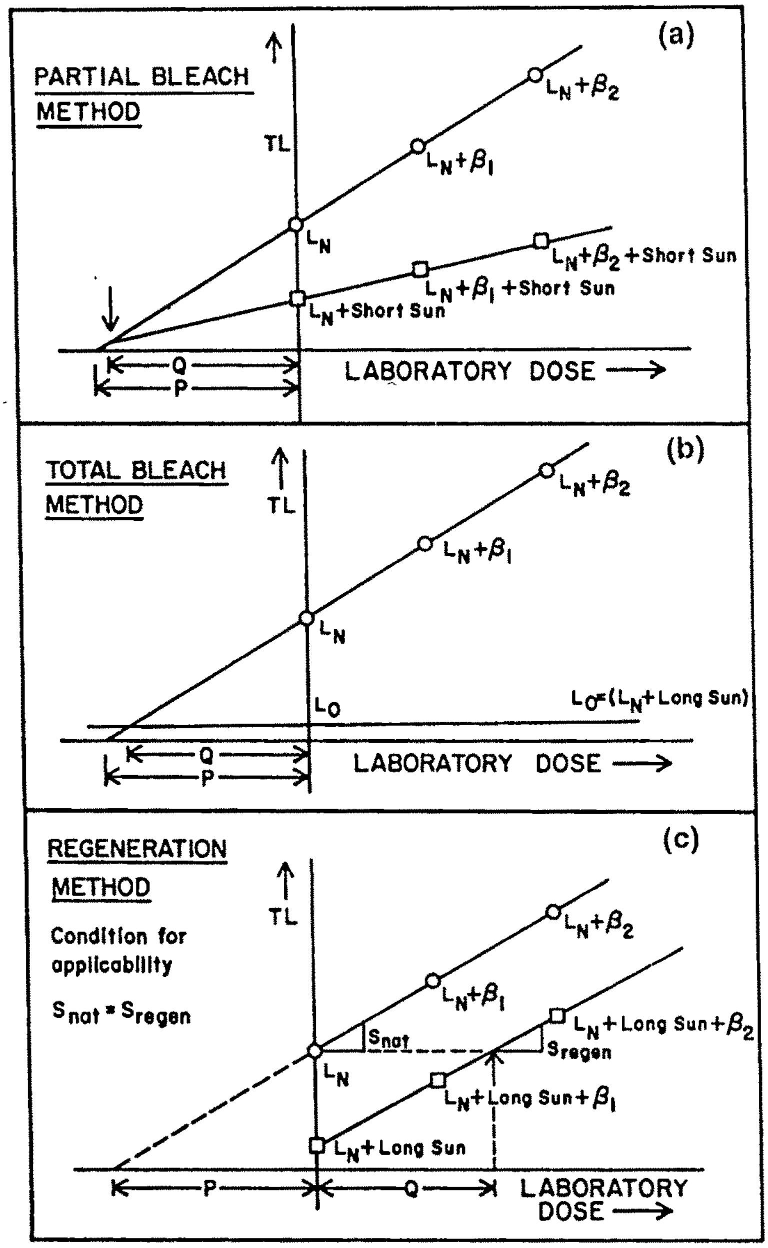

Fig 4.3 Schematic of methods used in estimation of equivalent dose for sediments. X-axis refers to laboratory dose (after Wintle and Proszynska, 1983).

incremental beta (or gamma) radiation, the samples are additionally given a short sun exposure prior to recording. On the basis that the amount of TL removed by the bleach is a given fraction of the bleachable TL, the intersection of a natural (unbleached) growth curve with the sun bleached curve provides the equivalent dose (Fig 4.3a). The equivalent dose remains unchanged as long as the laboratory sun exposure is smaller than the one received in nature; it increases rapidly once this limit is exceeded.

2. **Total bleach method** (Singhvi et al, 1982): The equivalent dose (ED) is calculated by constructing a TL/OSL growth curve with additive beta or gamma radiation and subtracting from it the residual level (Fig 4.3b) reached after long laboratory light exposure (12 hours), which is presumed to be similar to the level attained prior to deposition.

3. **Regeneration method** (Wintle and Proszynska, 1983): In this method the equivalent dose is determined by comparing the intensity of natural TL signal to the TL signal that is 'regenerated' by laboratory dose on samples which have been sun bleached in the laboratory. The laboratory dose that provides a TL intensity equivalent to that of the natural sample is taken to represent the equivalent dose (Fig 4.3c) provided it is independently established that the laboratory sun bleaching does not alter the luminescence response of the sample. This is checked by comparing slopes of both the additive (obtained by giving incremental beta doses to natural samples) and regenerated (obtained by giving incremental beta doses to sun bleached samples) growth curves. This method is mostly used for well light - bleached aeolian material in which the residual level was reduced to a low level prior to deposition.

Estimation of dose rate

Dose rate (DR) is a measure of environmental radioactivity of the sediment over a period of time. The estimation of dose rate is generally done using the elemental concentrations of U, Th and K which can be estimated using a variety of physical and radiochemical techniques. The calculated DR is corrected for absorption of alpha, beta and gamma radiation by water in the sediment. The possible sources of error in DR estimation are (i) long term variations in water content since burial, and (ii) disequilibrium in the decay series. Both of these are discussed subsequently in Section 4.1.4.

In case of OSL, a glance at Fig 4.2 suggests that the time required for zeroing is very short. Thus, in general, most of the sediments can be considered to have been well bleached as far as OSL is concerned. This implies that for OSL dating (Huntley et al, 1985) no correction for residual signal is needed and generally the additive growth curve is sufficient to obtain the equivalent dose. Experimentally, the approach is similar to that in the 'total bleach method' except that no correction for residual level is needed. As the present work was concerned with the dating of fluvial, proximally transported sediments, a brief survey of factors affecting bleaching and dose rate is given below.

4.1.3 Factors affecting the luminescence signal

This discussion is structured into two sub themes dealing with: (i) the factors influencing the effectiveness of luminescence zeroing prior to deposition, and (ii) stability of the luminescence signal.

Factors influencing the effectiveness of luminescence zeroing

For sediments transported and deposited by water, the extent of sun exposure and hence zeroing of geological luminescence depends on a variety of factors as water depth, sediment load, grain size, mineralogy, turbulence and duration of transport of sediments. A brief account of these follows.

Water depth: For water laid sediments there is an attenuation of solar spectrum due to absorption by water (Swain and Davis, 1978). Light in the UV to blue region of the spectrum is most effective in evicting electrons from traps but water severely attenuates UV radiation (Jerlov, 1976). Berger and Luternauer (1987), have demonstrated that light intensities at 4m depth in a turbid river are more than 10^4 times lower compared to the surface flux and the solar spectrum is severely attenuated below 500 nm and above 690 nm. In another study involving measurements of underwater spectra for waterlain sediments, Berger (1990), observed that in Lilloet lake (British Columbia), spectra down to 2m are more attenuated at both red and blue ends, with a peak in 560-590 nm range.

Sediment load: The net solar spectrum also gets attenuated and shifted towards the red region of the spectral band due to absorption and scattering by solid particulates in water (Jerlov, 1976). The sediment load also varies seasonally. In a study involving measurement of underwater spectra in Fraser river, British Columbia, it was found that, subsequent to a maximum annual discharge in May-June, there was a prominent red component, with a concomitant sharp attenuation of the blue green wavelength. In contrast, during the lower discharge in September, there was proportionately smaller red and larger blue components which have been attributed to differences in relative concentrations of detritus and chlorophyll, (Berger, 1990). In a laboratory experiment, Ditlefson (1992), exposed 2-11 μm size grains to solar spectrum through sediment suspensions (of 75 cm height) for different periods of time. It was found that, for dilute suspensions (0.01-0.02 g/l), more than 50% of TL signal remained after 20 hours of bleaching but infra red stimulatable luminescence was reduced to 5% in a similar set-up. In more dense suspensions (>0.5 g/l), there was little reduction in either TL or IRSL and bleaching times in excess of 20 hours were needed to reset the luminescence for dating. Thus, the suspended sediments within the water column not only caused spectral attenuation, but also resulted in partial or full filtering of wavelengths between 400-600 nm depending on the turbidity and depth from the surface layer.

Turbulence: Laboratory studies (Gemmel, 1985) have indicated that the rate of TL bleaching is inversely related to the speed of flow. Higher flow speeds result in lower photo-bleaching rates and vice versa. This was attributed to the effects of flow turbulence in keeping sediments in suspension, thereby reducing the penetration of UV radiation, and to the re-entrainment of partially bleached or unbleached sediments into the flow.

Grain size: Grains in an alluvial deposit may have been derived from different parts of the catchment area, e.g. from soils in the upper part of the catchment area, from actively weathering bedrock or from earlier alluvial deposits being reworked. During transport, different grain sizes are likely to have had different histories of light exposure on account of different sources, length and duration of transport, modes of transport and deposition. Fine grains are carried closer to the top of water surface and settle slowly; these have a greater probability of exposure to a wider spectra and getting bleached. The coarser grains being moved close to the river bed are likely to be exposed only to a restricted spectra (due to the effect of suspended sediment load and greater depth) resulting in insufficient bleaching. It is thus likely that the constituent grains, of different sizes, within the same deposit, may have had different degree of pre-depositional exposure and different residual levels of luminescence at the time of burial. In a study of known age glacio-lacustrine sediments of British Columbia, it was observed (Berger, 1988) that only the fine grained facies (clayey) which were deposited by slow rain out from suspension gave correct ages.

Mineralogy: It is now known that different minerals respond differently to photo-bleaching (Bailiff et al, 1977; Debenham and Walton, 1983; Mejdahl, 1985). Comparative studies of bleaching by sunlight for OSL and TL have been reported by Godfrey-Smith et al, (1988). They observed that for OSL, 1% of the initial signal was reached in 10 seconds for quartz and 9 min for a sample of feldspar. For TL, the minerals show a reverse sensitivity to bleaching (Fig. 4.2).

Foregoing discussion clearly brings out that in case of fluvially transported sediments, the extent of zeroing is uncertain. For such a dating effort, the TL partial bleach method which involves a very short sun exposure or OSL method is to be preferred. In cases where both the partial bleach and OSL methods have been applied to the sediments, a general agreement between the two was observed (Duller, 1992; Balescu and Lamothe, 1994; Rao, 1996). As an improvement to partial bleach method Berger (1990), recommended laboratory bleaching, after blocking the shorter wavelengths. This was successfully used in several instances for dating of partially bleached sediments. There are exceptions, however, where even the approach of restricted bleaching did not yield meaningful results in case of known age samples (Berger and Easterbrook 1993; Berger, 1988; Forman and Ennis, 1991).

Stability of the luminescence signal

Long term stability: Kinetic studies indicate that the high temperature (>250° C) TL signal of feldspar and quartz has a mean life of 1-10 Ma (Aitken, 1985). However, regeneration ages on fine grain fraction of loess from Europe showed an agreement with known ages only upto 50-100ka (Debenham, 1985; Wintle, 1985b). Beyond this, ages were consistently underestimated. Studies on IRSL dating of feldspars also indicated limiting ages (Rao, 1996). Debenham (1985), explained this underestimation in TL ages as being due to time dependent decay of luminescence centres. On the other hand Rendall and Townsend (1988), have attributed the underestimation effect to sensitivity changes resulting from exposure to laboratory light. Efforts have been made to correct the dates assuming a mean lifetime of TL signal (Debenham, 1985; Wintle, 1990).

Anomalous fading: Some samples exhibit, over a short time, a loss of signal which, on the basis of kinetic considerations, is expected to be stable over a much larger period. This phenomenon, called anomalous fading, was first reported by Wintle (1973). In some cases, loss of TL signal of even 50% over a storage period of one week has been observed. This obviously has important implications for dating as it substantially affects the ages. In particular, it was found that volcanic feldspars can show serious fading (Guerin and Valladas, 1980). Following explanations have been suggested to explain anomalous fading: (i) Tunnelling of charges from traps to recombination centres due to their volume overlap (Wintle, 1973;1977; Visocekas, 1979; Huntley, 1985a). (ii) Templer (1985), explained fading in zircons by suggesting that recombination proceeded via an excited state shared between traps and recombination centres. To facilitate isolation of stable signal, often a pre-heat at 150°C-200°C for times ranging upto few hours is used.

4.1.4 Factors affecting the dose rate

These are discussed below.

Water content: Water in sediments, though itself devoid of radioactivity, absorbs part of the radiation which would have otherwise reached the grains. Thus, the net radiation dose is lower than calculated from the abundance of U, Th and K in the sediment. Therefore, a correction to account for the higher stopping power of water for α, β, γ as compared to air is applied (Zimmerman, 1971). Although the amount of attenuation is calculated using 'as found' values, the variation of water content through geological time and its actual estimation constitute the single largest uncertainty. The saturation level, as determined by the porosity of the sample, sets an upper limit for this effect on age.

Disequilibrium effects: Another factor that effects the dose rate estimation is the disequilibrium in the decay series of U and Th. The two elements have long decay chains, involving radioisotopes with significantly different geochemistry. It is likely that given a specific geochemical environment, daughter members may be leached out or precipitated, e.g. U and Th have short lived gaseous member Rn in their decay series, as indicated below,

^{232}Th series: $^{220}Rn\ (T_{1/2} = 55.6\ s) \longrightarrow {}^{216}Po$

^{238}U series: $^{222}Rn\ (T_{1/2} = 3.83\ d) \longrightarrow {}^{218}Po$

^{235}U series: $^{219}Rn\ (T_{1/2} = 3.96\ s) \longrightarrow {}^{215}Po$

In each of the above cases, escape of the radon gas is a possibility. This process is speeded up by the action of water (Desai, 1975). If radon is lost then not only is the Rn activity less but activities of all subsequent members are also lower. Escape is more likely with ^{222}Rn because of its half life of 3.8 days. Others isotopes because of their short half lives are more likely to decay into non mobile daughters before escape. For 100% escape of ^{222}Rn, there is a 25% decrease in annual dose for fine grains (Aitken, 1985).

There can be other causes of disequilibrium too. Radium may be leached out by the action of ground water. Also, uranium and thorium occur in nature in tetravalent oxidation state and their ions have similar ionic radii (U^{+4}=1.05A and Th^{+4}=1.10A). Consequently the two elements can substitute extensively for each other. However, under oxidising conditions U forms the uranyl ion (valency +6) which forms water soluble compounds. Therefore, U is a mobile element under oxidising conditions and may be separated from Th which exists only in the tetravalent state and whose compounds are generally insoluble in water. In case of calcium carbonate, U is incorporated at the time of deposition but not thorium. Also, both ^{230}Th and ^{231}Pa form insoluble hydroxides so that these are removed from ground water as soon as they are produced. This can result in an excess of ^{230}Th in river sediments which is found to increase with a decrease in grain size (Scott, 1968).

4.2 Present Study

Samples from Nal Sarovar core were dated with OSL method using IR stimulation. The experimental procedures are discussed in Appendix E. A total of 11 samples were dated using IRSL method. Of these, two samples were additionally dated using partial bleach method.

4.2.1 Results

The results of luminescence dating are shown in Table 4.1. A few of the typical sample results are shown in Fig. 4.4 and Fig. 4.5. Fig. 4.4 shows the IRSL growth curve for sample N-143. The estimated ED is 55±5 Gy (Fig 4.4a). Fig. 4.4b shows the IRSL ages for different IR stimulation times. An average age of the sample over the plateau was computed as 47±8 ka. Similar results are shown for sample N-168 in Fig. 4.5 (a, b).

In some cases, where a sufficient amount of sample was available for processing, coarse grained IRSL dating was attempted; for N-102 (150-250μ) and N-127 (90-150μ). The IRSL data for coarse grains, however, showed a large scatter (~20%) between identically treated discs even after normalisation. Similar large data scatter was observed during partial bleach TL dating, using 10min of sunlight bleaching, on 4-11μ fraction of samples N-143 and N-102.

Table 4.1 Results of luminescence and dosimetry measurements on samples from Nal Sarovar core.

Lab. No.	Depth (m)	ED[1] (Gy)	U[2] (ppm)	Th[2] (ppm)	K[3] (%)	α efficiency 'a'	H_2O in situ (%)	Dose Rate[4] (Gy/ka)	Age[1] (ka)
N-99	3.90-3.93	88±5	1.25±.35	3.29±1.2	0.44	0.07	7	1.365	64±8
N-102	4.27-4.47	198±24	1.86±.55	5.86±1.9	1.17	0.06	7.4	2.501	79±12
N-105	4.77-5.22	257±5	1.4±0.6	6.3±2.06	0.98	0.07	7	2.276	113±8
N-127	9.07-9.20	40±4 (87)	0.78±.33	3.74±1.12	0.29	0.07	7.6	1.091	37±10 (80)
N-143	12.17-12.25	55±5	1.45±.33	3.67±1.13	0.22	0.05	5.8	1.167	47±8
N-167	18.25-18.35	251±18 (272)	1.8±.53	5.09±1.8	0.46	0.06	6.9	1.731	145±9 (160)
N-168	18.35-18.42	156±3	1.37±.26	2.34±.93	0.33	0.07	7	1.138	136±9
N-226	23.81-24.00	165±7	3.33±.84	5.89±2.8	0.59	0.06	12.7	2.372	69±9
N-288	32.78-32.90	227±9	2.86±.62	4.78±2.13	0.56	0.07	16.4	2.160	97±9
N-412	49.95-50.00	202±11	2.21±.56	6.28±1.91	0.47	0.06	9.8	2.00	101±10
N-424	54.65-54.85	156±11	1.89±.43	5.46±1.48	0.27	0.07	5.9	1.705	92±9

1. IRSL data for fine grained fraction. The figures in brackets indicate the values obtained using TL partial bleach (10min) method.
2. Measured by α counting.
3. Measured using Atomic Absorption Spectrometry.
4. The dose rate has been calculated using an average value of 'as found' and saturation water content.

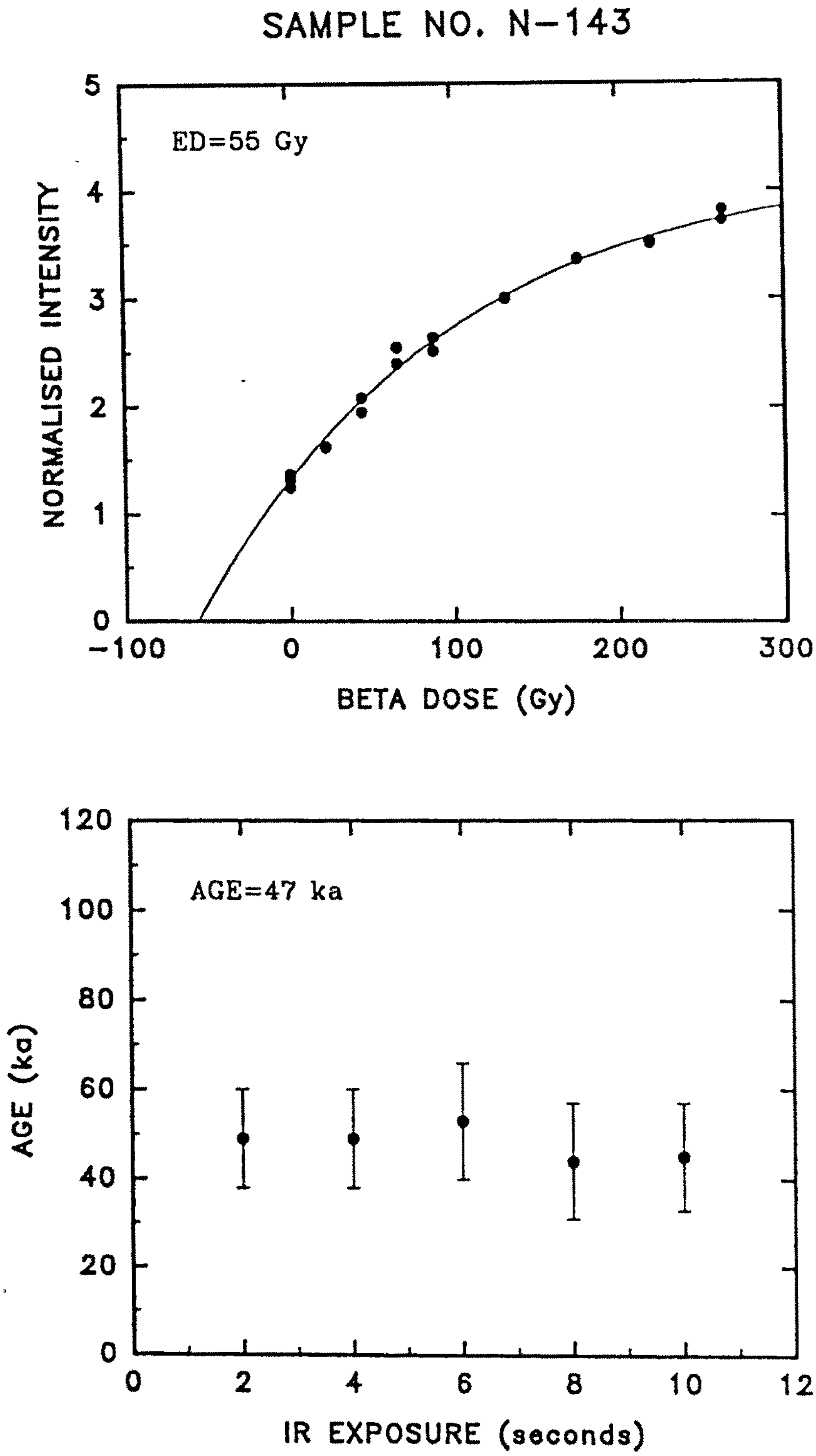

Fig. 4.4 IRSL growth curve and age plateau for N-143. Also indicated are the mean values of ED and age.

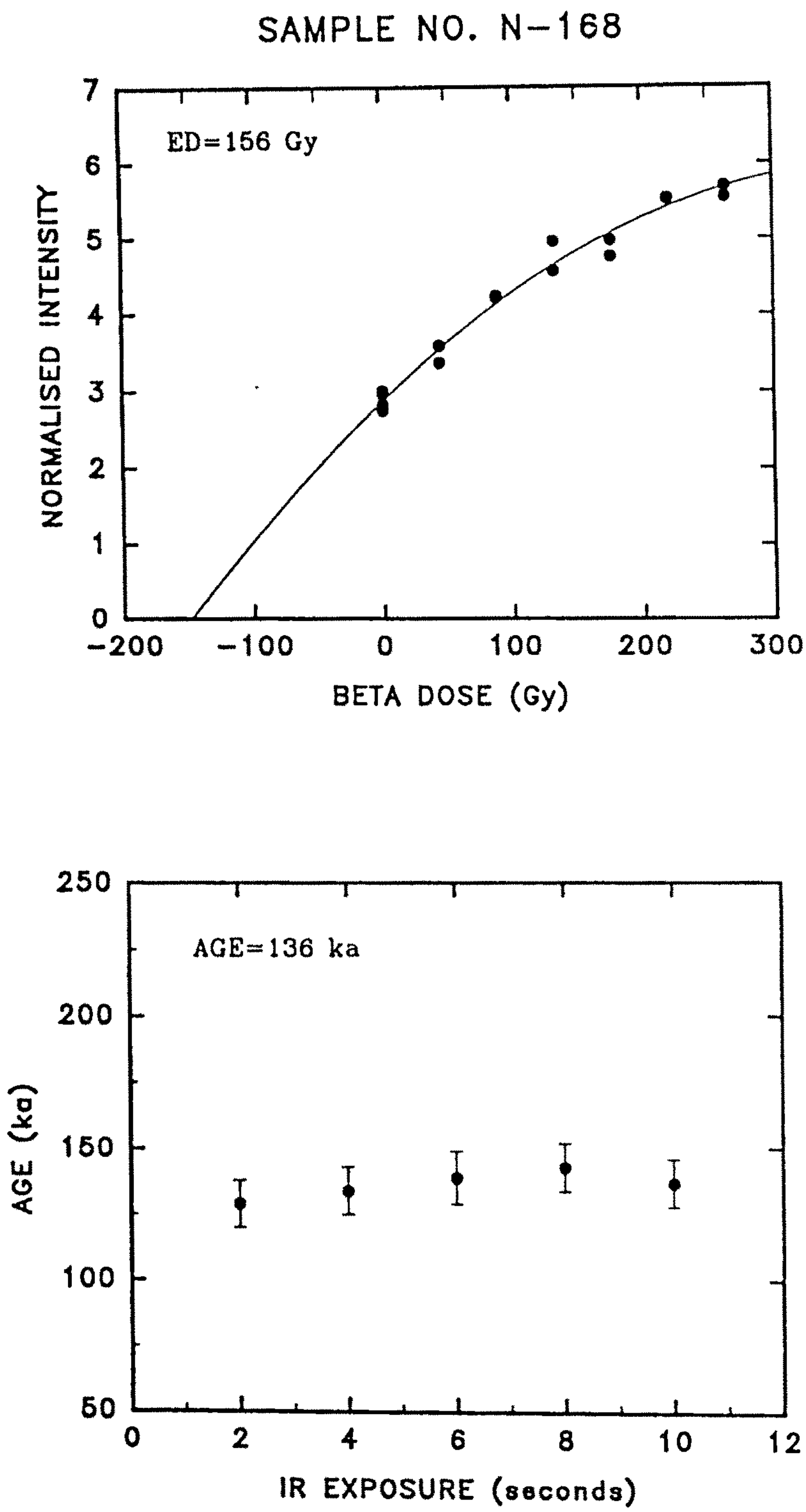

Fig 4.5 IRSL growth curve and age plateau for sample N-168. Also indicated are the mean values of ED and age.

This indicated that these samples contained a mixture of grains that were exposed to sunlight for very different periods of time. This could occur if, (i) distance of transport was very short or (ii) aeolian (well bleached) sediments were mixed with fluvial (partially bleached) sediments. When such samples are irradiated in the laboratory, the grains, being on different parts of their growth curves will show a large scatter in the TL/IRSL (Duller, 1994).

Both well bleached (dunes to east and north-east) and partially bleached (fluvial sediments to east) sediments could have acted as source for Horizon-2, of Nal Sarovar core, based on heavy mineral analysis (Section 2.2.3). But since the dunes were formed from reworked fluvial material, it is not possible, at this stage, to say which/both of these possibilities, namely, short distance transport or multiple sources could have caused the observed scatter in luminescence data.

The IRSL ages, on fine grained (4-11 μm) fraction of various samples studied, and their depths are graphically shown in Fig 4.6. An increase in dates with depth is observed though some samples give dates that do not follow the general trend line. The salient features of this study are discussed below.

4.2.1.1 Salient features of results

1. The samples in the sand layer (Horizon-2) showed a large scatter with some dates higher than the stratigraphically older Horizon-3 (Fig. 4.6). Also, the IRSL age of 79±12 ka at 4m depth is inconsistent with the radiocarbon age of ~7ka (Section 3.2.2) obtained on the organic matter at ~3m depth. This is because Horizon-2 grades into Horizon-1 and there is no evidence of a hiatus between the two.

2. An apparent saturation effect is visible in dates for Horizon-3, with the dates at ~32m and below hovering around ~90 ka.

3. Partial bleach TL dates, on 4-11μ size, with bleaching time of 10min, could be calculated for two samples in Horizon-2. The sample at 9m (N-127) depth

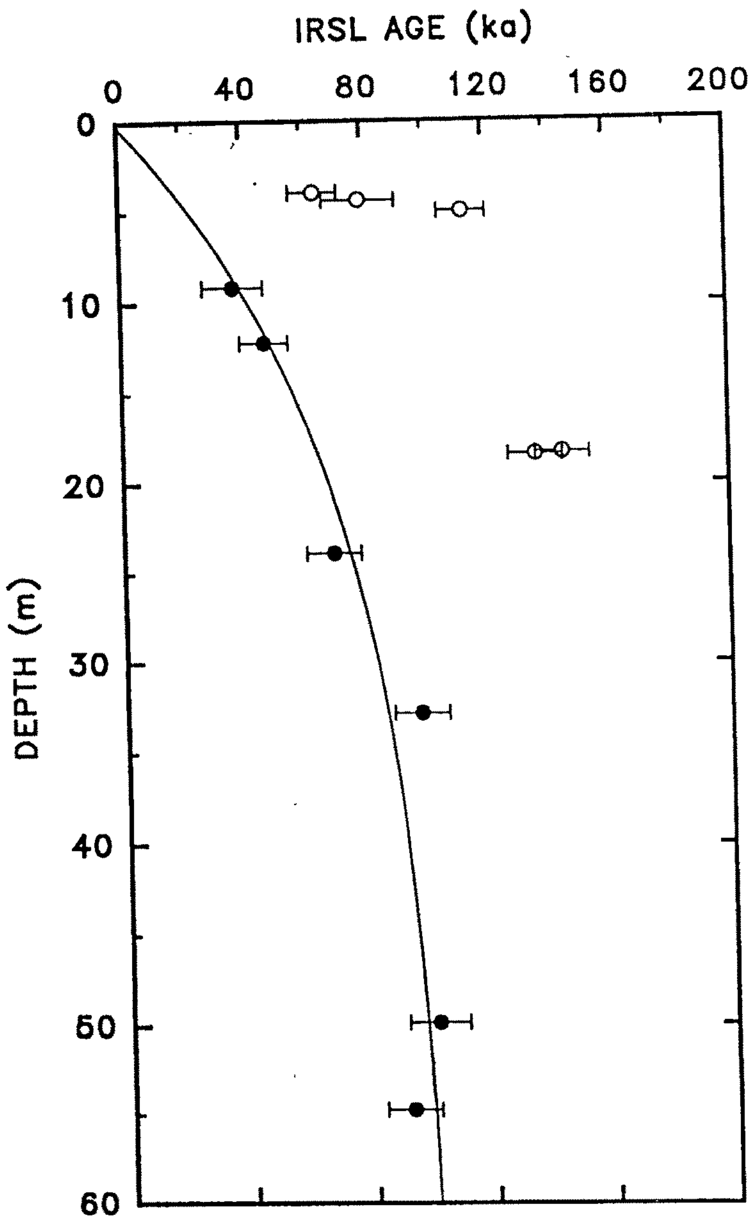

Fig 4.6 Variation of IRSL dates with depth in Nal Sarovar core. The open circles represent the anomalous dates (see text for discussion). The filled circles represent the dates used for interpolation.

gave a partial bleach date of ~80 ka which is higher than the IRSL age of 37±10 ka. Fig. 4.7 gives the results of partial bleach dating of the sample N-127. The TL glow curves for this sample are shown in Fig. 4.7a for different treatments of the sample i.e. N, N+S(10 min), N+220β. The additive and partial bleach growth curves at 340°C are shown in Fig. 4.7b. The age was estimated from the ED vs. temperature plot (Fig. 4.7c) over the plateau region 310°C to 350°C. Another sample at ~18m depth (N-167) was also TL dated using ten minutes partial bleach. It gave a partial bleach date of ~160 ka which is comparable to the IRSL date of 145±13 ka. Even though there appears to be an agreement between the IRSL and TL dates for the sample N-167, this date does not fit into the sequence. It appears that the sample at ~18.3m depth (N-167), had undergone little pre-depositional sun exposure and it is likely that these dates correspond to an older event prior to deposition in Nal. In contrast, the sample at ~9m (N-127) depth had been partially exposed to sunlight (probably a restricted spectrum) which, though sufficient to zero the geological IRSL, was not adequate to reset the geological TL.

An attempt was made to identify the cause of observed scatter in the IRSL dates on fine grained samples in the sand horizon (Fig. 4.6). In the earlier Section (4.1), it was noted that the age estimation could be affected by any one or more of the following: (a) anomalous fading, (b) disequilibrium in decay series, (c) variation in water content subsequent to burial and (d) insufficient zeroing of geological luminescence prior to deposition.

4.2.1.2 Tests for anomalous fading and disequilibrium

Tests on the samples (see Appendix E) with a storage of 3 months indicated an absence of anomalous fading. A typical anomalous fading test is shown in Fig. 4.8. It is seen that identically treated sample aliquots show, within narrow limits of scatter, no fading of signal even after 3 months storage.

Gamma spectrometry using HPGe detectors was undertaken to check for disequilibrium in the decay series of U and Th (see Appendix E). Disequilibrium was found to be absent in all cases. Only for samples N-167 and

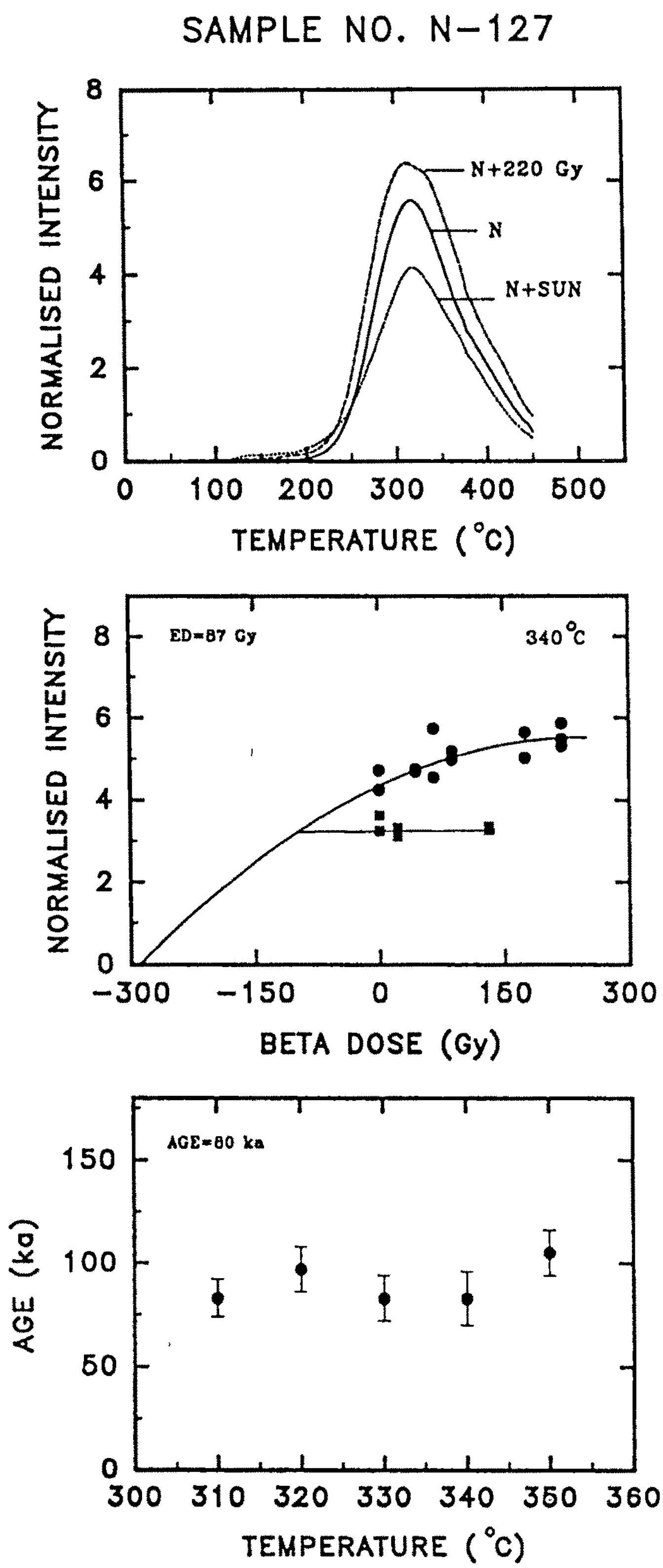

Fig 4.7 (a) Glow curves, (b) growth curves and (c) age plateau, for partial bleach dating (10 min sun exposure) of sample N-127.

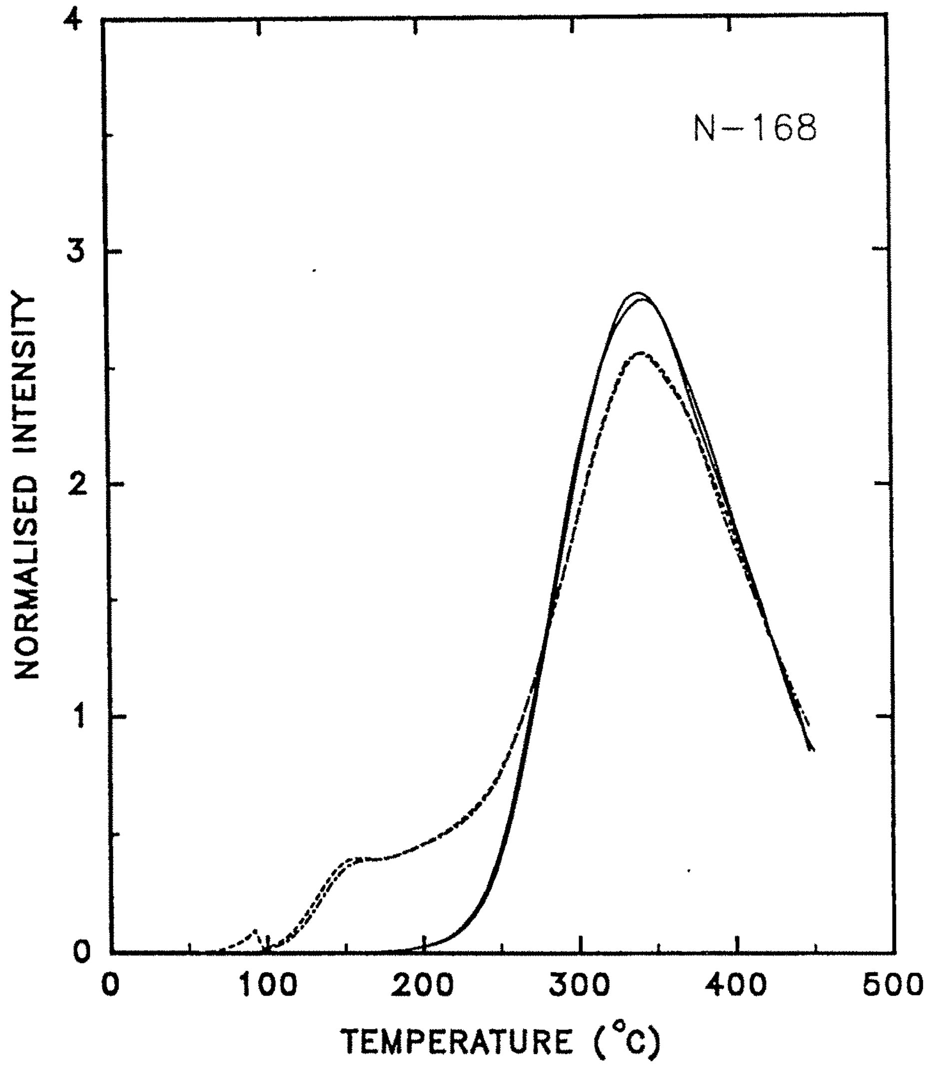

Fig 4.8 Result of anomalous fading test on a typical sample. The dashed lines show the TL of two aliquots immediately after irradiation of 44Gy. The continuous lines show the TL record of two other aliquots of the same sample similarly irradiated 3 months previously.

N-424, there is small difference in the U concentration as determined from peak intensities of ^{235}U and ^{214}Bi (Table 4.2); the two values, however, do not affect the IRSL dates significantly to explain the scatter.

4.2.2 Discussion

Saturation water content was determined for samples, one each from the sandy layer (16%) and silty clay layer (30%). A correction for dose rate, using saturation water content, was found insufficient to explain the observed anomaly in the IRSL age data beyond 20%.

The anomalous higher IRSL dates are confined to the sand horizon which was deposited by a high energy transporting regime. As discussed in Section 4.1.3, in case of transport in a dense suspension and/or turbulent transport, there is very little reduction of either TL or IRSL. Insufficient zeroing of the geological signal for such samples is a possibility. Such a possibility in case of Nal core samples was also indicated by the scatter in the coarse grained IRSL and fine grained partial bleach data of sediments from Horizon-2. Also, in the present case, an indication of higher energy of transporting medium was found in the coarser sand size of the samples showing anomalous ages as compared to the samples which lie on the trend line (Table 4.3).

To the east of Nal lies the Cambay Graben which is known to have experienced tectonic activity during the Late Quaternary (Sareen et al, 1993; Sridhar et al, 1994). The heavy mineral assemblage of the sand layer is typical of a mixed granitic and/or metamorphic provenance indicating that the source area for sand in the 4-18m layer, at least, has remained confined mainly to east and north-east of Nal Sarovar. A tectonically induced uplift in the Cambay Graben would result in the rejuvenation of the rivers which then begin to downcut previously deposited sediments. It is also possible that the sediments showing anomalous dates are reworked older samples which were deposited

Table 4.2 Estimation of U and Th on samples from Nal Sarovar core by γ counting in different parts of decay chain. Also given are the estimates from α counting.

Lab No.	U (ppm) - γ spectrometry				Th (ppm) - γ spectrometry					U (ppm)	Th (ppm)
	^{235}U (185)+	^{214}Pb (295)+	^{214}Bi (609)+	^{214}Bi (1120)+	^{212}Pb (238)+	^{208}Tl (583)+	^{228}Ac (338)+	^{228}Ac (911)+	^{228}Ac (968)+	α counting	α counting
N-99	1.15	1.43	1.37	1.33	4.98	4.94	4.94	4.73	4.01	1.25±0.35	3.29±1.2
N-102	1.56	1.4	1.62	1.54	6.4	6.8	7.33	7.19	6.32	1.86±0.55	5.86±1.90
N-105	1.43	1.54	1.5	1.35	5.3	5.17	5.15	5.27	4.23	1.40±0.6	6.30±2.06
N-143	1.16	1.15	1.28	1.15	3.6	3.44	3.59	3.31	3.27	1.45±0.33	3.67±1.10
N-167*	1.52	1.88	1.83	1.99	2.2	2.5	2.2	2.54	2.51	1.8±0.53	5.09±1.80
N-226	1.88	2.04	2.01	1.66	9.08	8.88	10.43	10.21	9.07	3.33±0.84	5.89±2.80
N-288**	1.74	1.78	2.03	2.39	10.81	11.11	13.26	11.91	10.79	2.86±0.62	4.78±2.10
N-412	1.87	2.06	2.32	2.18	10.47	10.88	12.6	10.68	10.11	2.21±0.56	6.28±1.90
N-424	1.45	1.84	1.81	1.87	6.7	6.83	7.38	6.79	7.04	1.89±0.43	5.46±1.50

Errors in measurement are 10%.

+ Numbers in brackets indicate the energy (keV) of γ emitted by the isotope.

* Th is underestimated by γ counting. IRSL age from Th (γ) is 173ka as compared to IRSL age of 145ka from Th (α).

** Th is overestimated by γ counting. IRSL age from Th (γ) is 80ka as compared to IRSL age of 97ka from Th (α).

Table 4.3 Mean grain size of samples from sandy horizon that have been dated by luminescence method.

Lab No.	Mean size	Sediment type	Measured IRSL date (ka)	Estimated* IRSL date (ka)
N-99	0.86ϕ	coarse sand	64	18
N-105	0.93ϕ	coarse sand	113	23
N-127	1.33ϕ	medium sand	37	38
N-143	1.16ϕ	medium sand	47	48
N-167	0.93ϕ	coarse sand	145	65

* Estimated from best fit to the minimum IRSL age vs depth data.

by flood events; these were inadequately zeroed prior to deposition and hence reflect older ages. Evidence of older exposed deposits, found in cliffy sections; entrenched rivers and fault controlled river courses, have been reported (Sridhar, 1995; Tandon et al, 1996).

Thus, in view of (i) absence of anomalous fading; (ii) absence of disequilibrium in the samples, and (iii) the possibility of inadequate pre-depositional zeroing, the minimum dates consistent with stratigraphy have been accepted. The dates of intermediate samples have been obtained by interpolation between the accepted dates. With this assumption, the measured IRSL age of the red bed at 12m depth in Nal Sarovar core is 47±8 ka. This is in agreement with the TL/OSL age 58±5 ka of similar red bed found at Vijapur near Ahmedabad (Tandon et al, 1996). This is significant since this red bed has a regional occurrence and is used as a marker horizon (Pant and Chamyal, 1993) for Late Quaternary deposits in Gujarat. The interpolated date of sample at 18m depth is ~65 ka indicating an age of >65 ka for underlying Horizon-3 which, fits in fairly well with the >73ka (isotope stage 5 age) assigned to this deposit on the basis of field evidence. Since all the dates below 32m hover around ~90ka, it is likely that this feature is due to saturation effect (see Section 4.1.3). The age determined for sample at ~54m depth (sample no. N-424) is 90±12 ka which is likely to older as it has been underestimated to some extent due to saturation effect.