Luminescence studies on the sediments laid down by the December 2004 tsunami event: Prospects for the dating of palaeo tsunamis and for the estimation of sediment fluxes

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The tsunami of 26 December 2004 was associated with an *Mw* 9.3 earthquake. This was the second largest earthquake ever recorded. Geodynamic processes leading to such earthquakes suggest that these are repetitive. It is therefore desirable to obtain their recurrence interval. Earlier attempts to date palaeo-tsunami sediments have assumed that the basic premises for the use of optically stimulated luminescence (OSL) are adequately met. The sediments transported by the 2004 tsunami provided a maiden opportunity to verify the basic premises of the zeroing of the luminescence at the time of deposition. Results on eight of the nine samples using the conventional single aliquot regeneration (SAR) method provided OSL palaeodoses in the range 0.5 to 0.7 Gy. The recently developed component-specific SAR (CS-SAR) consistently provided OSL palaeodoses in the range 0.5–0.7 Gy. Further, CS-SAR consistently provided evidence that in eight of the nine samples, a fraction of the sample did experience daylight bleaching during transport with the tsunami. This was suggested by the fast-component OSL palaeodose of ~0.2 Gy. This implies a maximum age offset of ≤ 50 yrs and suggests that despite its energy and wave amplitude, only the top ~20–50 cm layer of the sediment in the intertidal zone was mobilized. This inference can be used for sediment influx calculations and hence for regional disaster management.

Keywords: Coastal dynamics, luminescence dating, quartz, tsunami.

THE study area covered a 200 km track along the Pichavaram–Chennai transect (13°.08′N, 80°19′E to 11°27′N, 79°47′E). Satellite remote sensing LISS III data were used to delineate the geomorphologic units. The physiography of the study area is a low, slightly undulating terrain with a general slope of 1° to 0.30′ towards the east coast of Tamil Nadu. The beach is narrow, and within few tens of metres from the shoreline, the elevation reaches a local maximum of ~ +1 m asl. Moving landwards, the profile rises to +2 m over a distance of ~800 m from the shoreline. Along the transect, four major zones within the tidal flat were recognized, viz. an outer sand flat merging with the beach dunes complex and rock exposures, middle sand flat, sandy to silty inner flats (mixed flats of Reineck and Singh[1], and salt marsh). The tsunami samples were collected along the entire transect of East Coast Road (Figure 1). This area is covered in the Survey of India toposheets for the region bounded by 79°45′E; 11°45′N and 80°00′E; 12°15′N. The samples and their location are given in Table 1. These are tsunami-affected sites that suffered significant damage. The tsunami waters rose to nearly 25–30 m[2,3], inundated river mouths and tidal flat zones for nearly 3 h and deposited a sand sheet of thickness up to 100 cm. The tsunami-laid sands extended inland from 80 to 1500 m. The thickness of the sand decreased after 400 m inland. The samples were from areas away from human interference and were collected by inserting metal pipes into the sands about 10–15 cm below their surface, with due care to avoid any daylight exposure. These being recently laid tsunami deposits, the field identification was straightforward.

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Table 1. Luminescence and radioactivity data on tsunami-laid sediments. Dose rate estimate was made using thick source alpha counting and gamma ray spectrometry. Radioactive equilibrium was assumed. Number of aliquots indicates number of sub-samples that were analysed to construct the palaeodose distribution. Errors in the last column are only computational errors. The total error, however, will be higher and can be reduced by improving the statistics by analysing a larger number of aliquots

Site nos	Locality	Sample code	Number of aliquots	Dose rate (Gy/ka)	P(Gy) SAR	P(Gy) SAR-Fast Comp (mean)	P(Gy) Min value fast component
1.	Coovum River mouth	CVR	20	1.9 ± 0.1	0.55 ± 0.01	0.5 ± 0.2	0.20 ± 0.03
2.	Marina Beach	MGR	25	2.5 ± 0.1	0.65 ± 0.01	0.5 ± 0.2	0.1 ± 0.1
3.	Sreenivasapuram	SNP	25	2.2 ± 0.1	0.69 ± 0.01	0.6 ± 0.2	0.37 ± 0.05
4.	Foreshore Estate	FRS	25	1.7 ± 0.1	0.57 ± 0.01	0.5 ± 0.1	0.09 ± 0.04
5.	Pattinapakkam	PTM	25	1.7 ± 0.1	0.70 ± 0.01	0.6 ± 0.2	0.27 ± 0.05
6.	Eliot's Beach	EB	25	2.0 ± 0.1	0.63 ± 0.01	0.6 ± 0.2	0.04 ± 0.03
7.	Kokklimedu near Kalpakkam	MKN	20	2.4 ± 0.2	0.53 ± 0.01	0.5 ± 0.2	0.02 ± 0.03
8.	Porto Nova	NGP	25	2.6 ± 0.2	0.78 ± 0.01	0.7 ± 0.1	0.56 ± 0.02
9.	Pichavaram	PCN	20	1.5 ± 0.1	1.68 ± 0.02	Not possible	Not possible

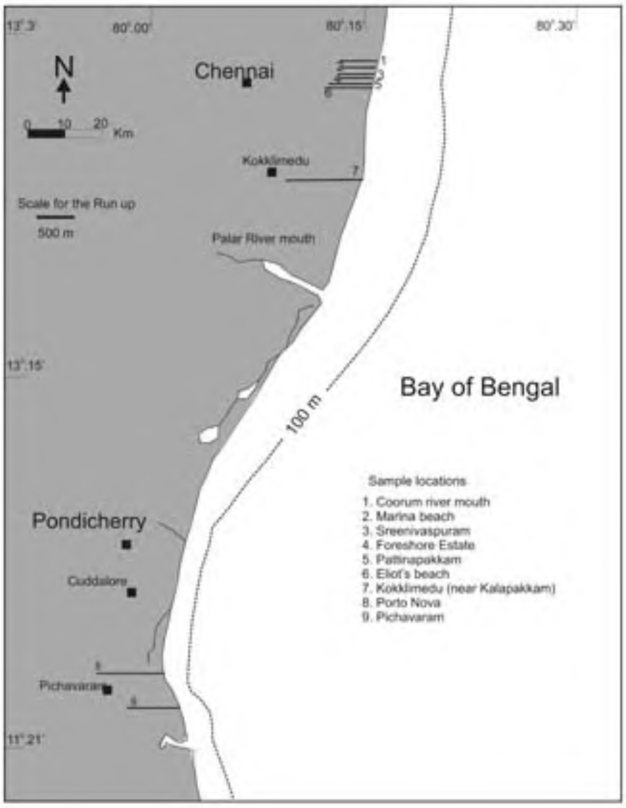

Figure 1. Coastal area and the sampling localities (1–9). Horizontal lines indicate the run-up elevation. Dotted line indicates the 100 m depth contour. Modified after Chaddha *et al.*[3].

Luminescence dating relies on the use of natural minerals such as quartz and feldspar as the radiation dosimeters of natural radiation environment (NRE). NRE arises due to the decay of naturally occurring radionuclides, viz. U, Th and K. In addition, cosmic rays provide a minor but finite contribution. The event dated is the most recent burial event. Minerals constituting the sediment stratum are exposed to daylight prior to deposition and this exposure photo-bleaches the geological luminescence of minerals, to a near-zero residual level. On burial, daylight exposure ceases and re-accumulation of luminescence due to irradiation from ambient radiation environment, begins. This re-accumulation continues unabated till excavation. Measurement of total absorbed radiation dose since burial (termed palaeodose P, measured in radiation units, Gy), is done via optically stimulated luminescence (OSL). Analysis of the radioactivity concentrations of the sediment enables computation of the annual radiation dose (D, measured as Gy/ka). The ratio (P/D) provides the burial age. Ubiquity of quartz and feldspars implies that most quaternary sediments for which a pre-depositional daylight exposure of a few minutes can be assumed are dateable using luminescence techniques[4].

A key aspect of luminescence dating is the pre-depositional zeroing of luminescence. This is because any attenuation of daylight in terms of its spectrum and flux reduces the bleaching efficiency drastically, requiring longer bleaching times. In short-lived sediment transport events like the tsunami, such an exposure may not be available. In such cases photo-bleaching at grain level is incomplete and heterogeneous. Measurement protocols now permit working with such samples and enable an isolation of the most bleached grain fraction. This is done by analysing several multiple sub-samples (at times up to single-grain level) and measuring and analysing the distribution of palaeodoses[5]. Earlier, limited luminescence dating efforts to date palaeotsunamis[6], provided stratigraphically reasonable ages in the range 260 ± 20–1200 ± 95 a. However, truly 'zero age' tsunami samples have so far not been analysed. The recent tsunami event provided a unique opportunity to examine the extent of zeroing and hence the first possibility of establishing the 'zero error', if any, in the application of OSL for the dating of palaeotsunami events. The sediment transport associated with the tsunami was rapid, copious and lasted for about 3 h.

The samples were pretreated with 10% HCl to remove carbonates and H_2O_2 to remove organic matter. This was followed by sieving to obtain 150–210 μm size fractions, heavy liquid density separation using sodium polytungstate (ρ = 2.58 g/cm^3), and HF (40%) etch for 80 min to

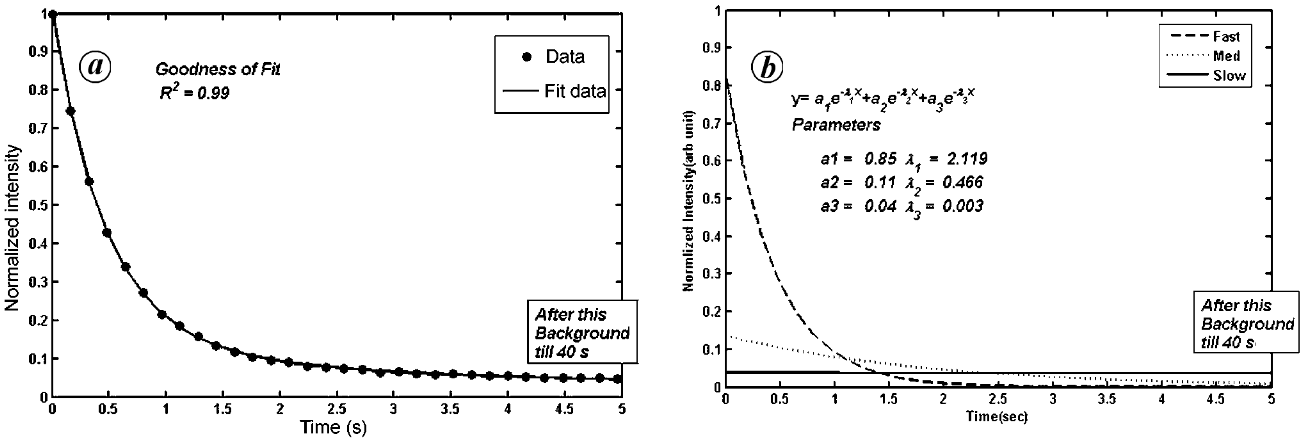

Figure 2. *a*, Decay OSL of quartz grains extracted from tsunami sands. Both the measured shine down curves (filled circle) and the fitted curves (solid line, based on a fit to a sum of three exponentials) are shown. *b*, Components of OSL decay of quartz from tsumani-laid sands. In this case the curve could be fitted as a sum of three exponentials. *a* is amplitude and λ is the decay constant.

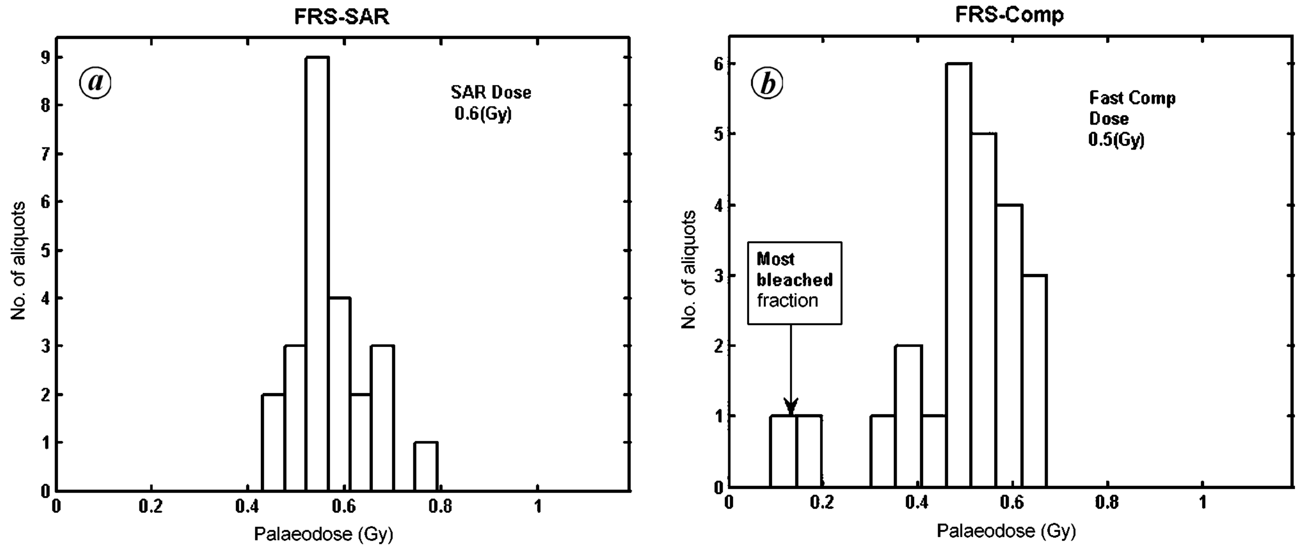

Figure 3. *a*, Distribution of palaeodoses measured using the SAR protocol. *b*, Palaeodose distribution using fast component of the OSL decay. A comparison with (*a*) indicates the presence of a low palaeodose component.

remove alpha-irradiated skin[4]. The purity of quartz with respect to feldspar contamination in the samples was checked[7] using infrared-stimulated luminescence and those contaminated were re-etched for a further 10 min. Samples were measured using a Risoe TL-OSL reader (TL-DA-15) with blue LEDs stimulating at 470 nm. The detection optics comprised Hoya U-340 and Schott BG-39 colour glass filters coupled to an EMI 9235 QA photomultiplier tube. The irradiations were made using a 40 mCi $^{90}Sr/^{90}Y$ beta source. A preheat of 240°C, 10 s and a cut heat of 200°C were used. The equivalent dose was estimated using the single, 2 mm aliquot regeneration (SAR) procedure of Murray and Wintle[8] and the extraction of component-specific SAR palaeodose using the procedures by Madhav *et al.*[9]. Only aliquots with a recycling ratio of 1 ± 0.1 were used. The dose recovery test indicated that luminescence from the samples was well behaved and the recovered doses were within the experimental errors (<4%). In the component-specific analysis, the OSL decay curves for individual aliquots were deconvoluted and the amplitude of the fast component was used to compute the palaeodose. Figure 2 *a* and *b* shows typical results. Table 1 summarizes the luminescence data and Figure 3 *a* and *b* provides typical dose distributions using the two protocols.

P from SAR on eight samples varied between 0.53 ± 0.01 and 0.78 ± 0.01 Gy. The mean fast component *P* varied from 0.5 ± 0.2 to 0.7 ± 0.1 Gy. The consistency in the *P*s from the conventional SAR and the fast-component SAR suggests that the samples were well-bleached before deposition during the tsunami. Conventionally, in a short-lived, high-energy sediment-transport event, durations over which the daylight exposure can occur are limited. The consistency of the OSL palaeodoses, therefore,

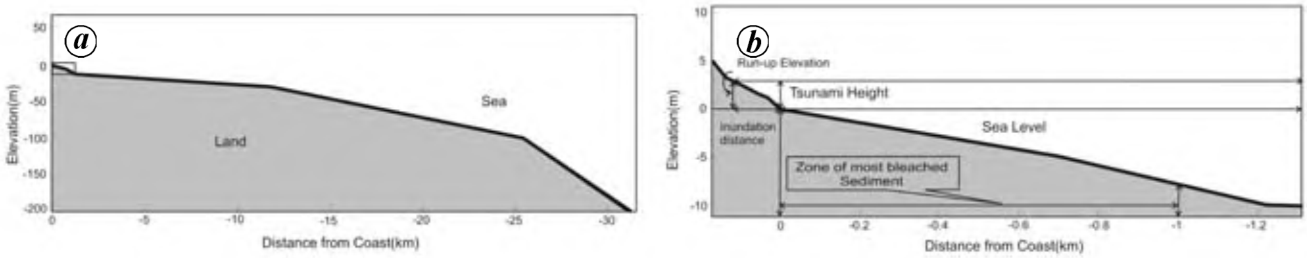

Figure 4. *a*, Approximate bathymetry of the region. *b*, Approximate bathymetry of coast near Nagapattinam. The zone of most bleached sediments comprises sediments up to a depth of 10 m and in the intertidal zone.

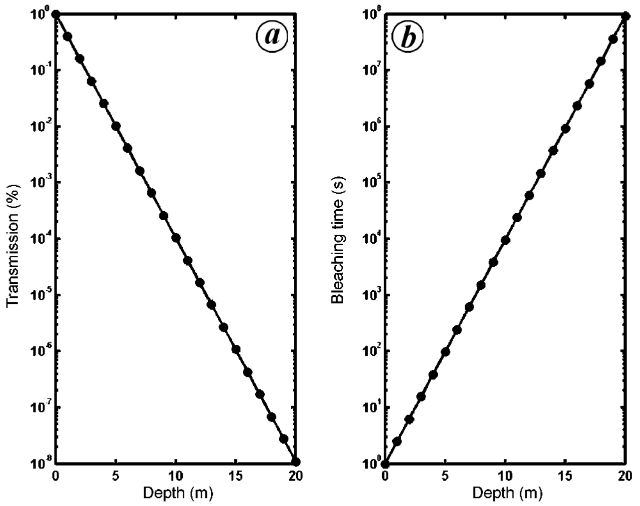

Figure 5. *a*, Transmission of light in coastal waters with high turbidity. Notice that the transmission spans eight orders of magnitude. *b*, Bleaching time required for a 50% reduction of OSL signal at various depths based on data provided by Aitken[4] and Jerlov[14].

suggests that the tsunami picked up only the near-surface sands residing in the sediment–water interface region of the intertidal zone, transported them landwards and deposited them (Figure 4). This is because, in the tidal regions, constant reworking of sediments ensures that they are exposed to daylight, which bleaches their OSL to a low, near-constant residual value. In these regions, sediment stratification also occurs and published results on sediment cores from the tidal zone indicate young ages on the surface immediately followed by ages of ~1 ka or more[10,11] at depths. Radiocarbon ages from the study area also show an abrupt increase in age with depth. For example, at Mammallapuram, sample AA30024 from a depth of 45–50 cm, yielded a radiocarbon age of 1620 ± 110 a BP. Similarly, sample BS 1608 from Marakkanam[12], near Pondicherry at depth 86–88 cm yielded a radiocarbon age of 1563 ± 130 a BP. If the tsunami had excavated older layers of the tidal region, then due to the possibility of limited bleaching during tsunami transport, a larger scatter in the palaeodose distribution of modern tsunami should have been seen (due to a mixing up of upper bleached and lower older samples with higher palaeodose). Thus a narrow dose distribution in samples, laterally spread over 200 km, indicates that no admixture from beach dunes or older deposits (under water) occurred.

Given that the present tsunami was one of the most energetic events ever, it then seems reasonable to suggest that despite their ferocity, tsunamis in general can rework only the top 50 cm or less, of the intertidal region. The implication of this will be the estimation of an upper bound to the sediment flux that can be transported by a tsunami event. This may be a useful input to the sediment flux estimation for various inundations scenarios. This aspect is easily tested using Figure 5 and by earlier studies. Berger and Luternauer[13] observed that (i) daylight intensities at 4 m depth in turbulent river waters were about 10^4 times lower than those at the surface, and (ii) the daylight spectrum was severely attenuated below 500 nm and above 690 nm. Attenuation factors for 500 nm light for high turbidity coastal water by Jerlov[14] are given in Figure 5. For this case, only ~1% of light of wavelength 500 nm is transmitted to a depth of 5 m. Assuming a proportional reduction in bleaching, it would take about 3 years at 20 m depth for highest turbid coastal water to get 50% reduction in signal. The depth of the sediment underwater is given in Figure 4. If 10 m is taken as a working limit where bleaching could proceed satisfactorily, then it is clear that only sediments that occur within a coast normal distance of a ~1 km should have seen daylight. This implies that for a metre along the coastline, the amount of sediment that can be potentially transported, will be the surface sediment lying in the 1 km coast-normal region, i.e. (1000 m × 0.5 m (maximum depth to which bleach sediment resides) × 1 m, i.e. ~500 m^3). This is similar to the measured thickness of sediment transported inland[15]. This estimate can be refined further by measuring the OSL of samples from cores underwater and by measuring the suspended sediment load and its OSL level.

Analysis of the components of the OSL decay curve provided further insights. Comparing the fast-component and bulk standard SAR palaeodose distribution also indicates that the fast component consistently has a palaeodose 0.02 ± 0.03 Gy. This is the fraction that suffered a finite daylight exposure during the short-duration transport and sedimentation. While the statistics is low, consistent presence of this behaviour in the samples suggests that there is indeed a bleached signal in the sample. Should this be so, the zero error in the age will be < 50 a. This will be an improvement on the mean SAR age of < 250 a.

We thus conclude that with recently developed component-specific OSL dating techniques[9], it is possible to date tsunami events with reasonable accuracy. It is also possible to use luminescence dating to provide constraints on sediment influx during such events. A set of analysis on drilled cores in tidal region and modelling of the equivalent dose behaviour as a physical mixing of two end-members can help in quantifying the potential transportable sediment volume.

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