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Research Paper

# Refining the OSL age of the last earthquake on the Dheshir fault, Central Iran

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ABSTRACT

In Central Iran there are several cities along the Dehshir fault, which have similar geological conditions to that of the city of Bam prior to the 2003 earthquake (Mw 6.5), during which more than 30,000 lives were lost. Optical stimulated luminescence (OSL) samples were collected from the Dehshir fault in order to place constraints on its seismic history. The single aliquot regenerative (SAR) dose measurement protocol on coarse grained quartz extracts was used for this study. This SAR protocol had to be optimized for the low OSL sensitivity by varying both the preheat temperatures and test doses used. Dose recovery tests showed that given laboratory dose could be successfully recovered. However, replicate palaeodose ($D_e$) data were scattered and consequently ages based on mean $D_e$'s had large uncertainties. As this is thought to largely reflect poor bleaching conditions prior to sediment burial at the site, various statistical procedures were employed in conjunction with the stratigraphic knowledge of the site to try and extract more refined burial ages from the samples. From this the timing of the last earthquake was estimated around $2.0 \pm 0.2$ kyr. This refined age suggests that the earthquake catalogue of Iran is incomplete and more paleoseismological investigation is required to recognize and date the previous events of Dheshir fault.



## 1. Introduction

Iran is one of the most seismically active regions along the AlpINE Himalayan belts, with numerous destructive earthquakes recorded both historically and instrumentally. Active tectonics in Zagros and Central Iran involves a combination of strike-slip and thrust faulting (e.g. Jackson and McKenzie, 1984; Berberian and Yeats, 1999). The Dehshir fault is the westernmost strike-slip of a series of N-striking dextral faults that slice Central and Eastern Iran (Fig. 1). This right-lateral fault is around 380 km long and trends NNW–SSE between 29.5°N and 33°N (e.g. Berberian, 1981; Walker and Jackson, 2004; Meyer and Le Dortz, 2007; Fig. 1). Meyer et al. (2006) estimated the slip rate (#2 mm $yr^{-1}$) of the right-lateral Dheshir fault using geological and geomorphologic offsets.

Despite of the above mentioned works, there is little information about the timing of past earthquakes and the recurrence interval produced by individual faults in the region. Luminescence dating is one of the most suitable dating methods for arid zones like Iran. Worldwide, it has been successfully applied to earthquake related sediments (e.g. Pucci et al., 2008; Porat et al., 2007; Vandenberghe et al., 2007; Mathew et al., 2006; Fattahi, 2009 and references there in). In Iran, whilst previous work in the north east of the country has shown that infrared stimulated luminescence (IRSL) from feldspar can provide reliable ages (e.g. Fattahi et al., 2006 and 2007; Fattahi and Walker, 2007) the application of optically stimulated luminescence (OSL) dating has been limited and problematic due to limited quartz, weakness of OSL signal, unconventional signal behaviour and partial bleaching. This study builds on the work of Nazari et al. (submitted for publication) who collected OSL samples from the Dehshir fault for seismic hazard risk assessment. They suggested a minimum slip rate of 0.7–2.6 mm $yr^{-1}$; found evidence for several paleoearthquakes; and estimated a rough return period of several thousands years for earthquakes; with a magnitude of $M \geq 6.5$. However, the OSL ages presented by Nazari et al. were based on a weighted (by inverse variance) mean calculated from a scatter palaeodose ($D_e$) distribution and consequently had large uncertainties. As a result Nazari et al. could only conclude that the last earthquake occurred

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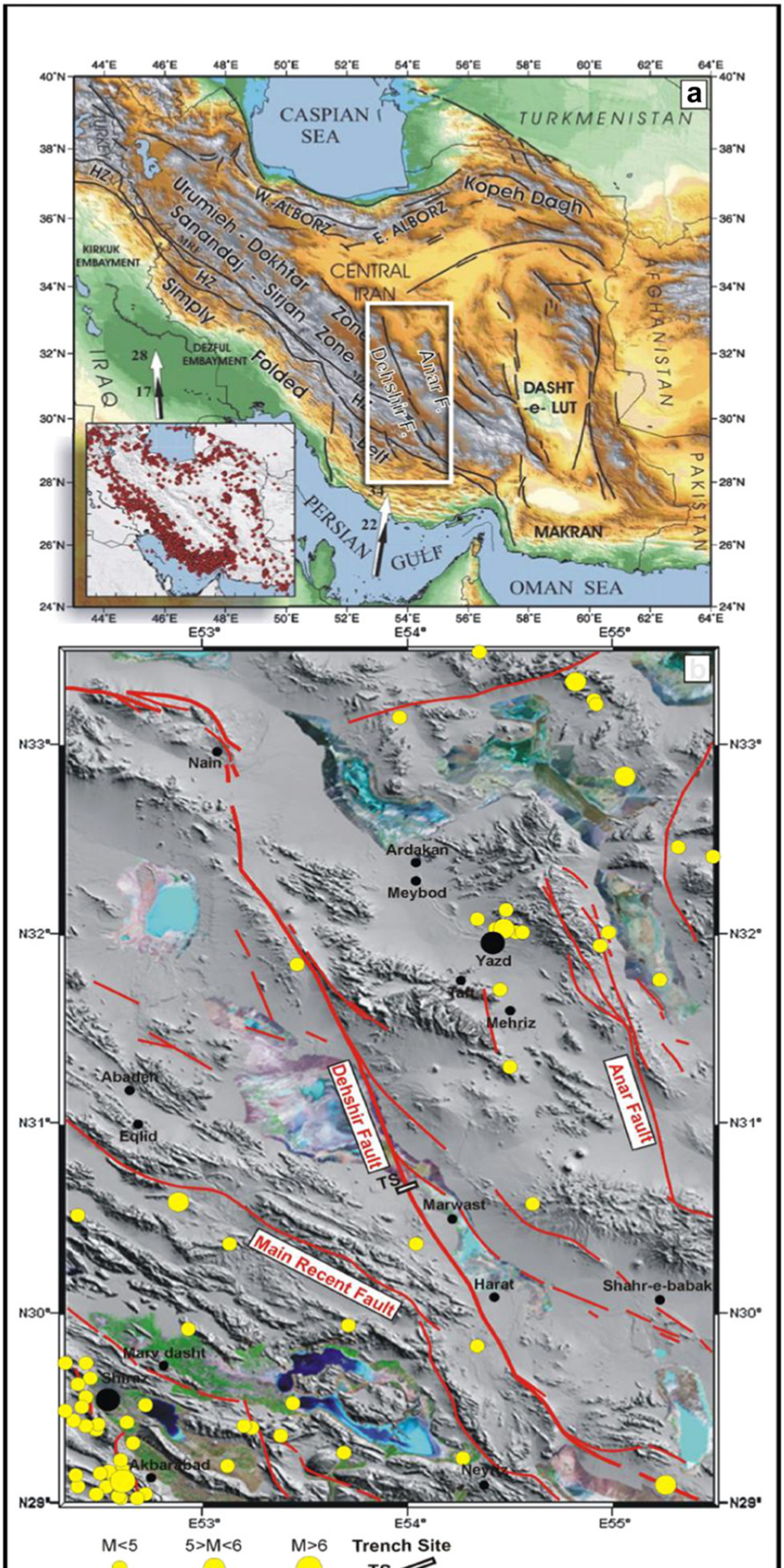


**Fig. 1.** (a) Simplified map of active faults of Iran from Talebian (2003). Inset shows the instrumental seismicity from Engdahl et al. (1998) (mb > 5). Black and white arrows are velocity vectors in a Eurasian fixed frame from REVEL (Sella et al., 2002) and NUVEL1A (DeMets et al., 1994) global plate models, respectively. (b) Seismotectonic map of Dehshir fault shown by rectangle in (a) with 1973–2008 seismicity from NEIC (http://neic.usgs.gov/neis/epic/). Background image is from SRTM data (http://edcsgs9.cr.usgs.gov/pub/data/srtm/) supplemented with Landsat images.

sometime between 1.4 and 4.2 kyr. This study aims at refining the analytical procedure used by Nazari et al. (submitted for publication, Terra Nova) to narrow the large errors on calculated ages. This appears critical for a better assessment of the seismic hazard and allows developing a protocol appropriate to date fluvial and colluvial material from Iran.

## 2. Study site

Following each surface rupturing earthquake, material eroding from fault scarps supplies colluvial deposits which fill open fissures or mantle the fault scarps. A trench excavated through the Dehshir fault at 30:38:28N 54:01:17E revealed clear evidence for recent faulting of young alluvial fanglomerates and subsequent colluvial units (see Nazari et al., submitted for publication for details). The uppermost layer, a silty sandy colluvial deposit, fills a set of open fissures which were caused by the last earthquake (Fig. 2). Therefore, the age of this colluvial sediment provides a valuable constraint on the last seismic activity of the Dehshir fault, which, when combined with estimates of the likely interval between large earthquakes, provides critical information on the earthquake hazard level for the region. One sample (Hi2006II) was collected for OSL dating from the uppermost layer of this colluvium which should have been completely reset if deposition of this post faulting sediment was sufficiently slow (Fig. 2). Two other samples (Hi2006I, Hi2006VI) were collected for OSL dating from two other layers for stratigraphic and technical control. The samples were collected using stainless steel tubes (5 cm by 25 cm) and both ends were sealed and covered using both aluminium foil and black tape.

## 3. Experimental details

All samples were prepared in the Sheffield Centre for International Drylands Research luminescence laboratory. Samples were opened in the laboratory under red light conditions. Five centimetres of each end, which was presumably exposed to light during sampling, were used to determine sample moisture content and for inductively coupled plasma mass spectrometer (ICP-MS) analysis of uranium, thorium and potassium concentrations carried out at SGS laboratories, Ontario Canada. Annual dose was estimated from these data and was attenuated for grain-size measured, palaeomoisture (based on present-day values) and cosmic contribution (see Fattahi et al., 2007).

The middle part (light unexposed) of each tube was used for the $D_e$ determination. The single aliquot regenerative (SAR) dose protocol of quartz (Murray and Wintle, 2000, 2003) was applied to aliquots of 90–150 μm quartz, which were prepared by sieving, HCl and $H_2O_2$ treatment, followed by heavy liquid separation (<2.7 g/cm$^3$), HF for 60 min, HCl retreatment, resieving and finally a check with IR stimulation for feldspar contamination. All the experiments reported here were carried out using a Risø automated TL/OSL system (Model TL/OSL-DA-15; fitted with a $^{90}$Sr/$^{90}$Y beta source delivering $\sim$3.2 Gy min$^{-1}$) equipped with an IR laser diode and blue LED as stimulation sources. OSL was detected using an Electron Tube bialkaline PMT. Luminescence was measured through a 7 mm Hoya U-340 filter.

## 4. Luminescence characteristics

The suitability of the samples for the SAR protocol was tested by examining its luminescence characteristics such as thermal transfer and dose sensitivity, through quality control procedures on the SAR data and via dose recovery tests (Murray and Wintle, 2003).

### 4.1. OSL responses

The samples used for this study were very insensitive to dose and suffered from a weak OSL signal (between 30 and 250 counts per Gy per sec for a 9.6 mm diameter aliquot). Initial attempts to measure OSL at the single grain level therefore proved futile and as a consequence measurements were made on 9.6 mm diameter aliquots. Only at this level was it found that there was sufficient natural OSL to measure above background. Normally the test dose within SAR is kept to where it is only a small proportion ($\sim$10%) of the dose naturally acquired during burial. However, the low OSL sensitivity precluded this approach for these samples. As a result we also applied a range of different doses to the samples and analysed the OSL response levels to choose a test dose. Selection tried to minimize the size of the test dose to avoid any impact on subsequent regeneration points within SAR whilst providing sufficient OSL to properly monitor sensitivity changes. This resulted in a test does of 6 Gy being used for all measurements.

### 4.2. Thermal transfer

To test if there were problems from the thermal transfer of charge into the OSL trap as a result of preheating, natural aliquots were stimulated at room temperature without any prior preheating and OSL was measured for 100 s. After more than 4 h delay the OSL was measured again. No significant OSL signal was observed for the second measurement. Then, SAR was applied to measure the $D_e$ at different preheat temperatures (expected to be zero in ideal

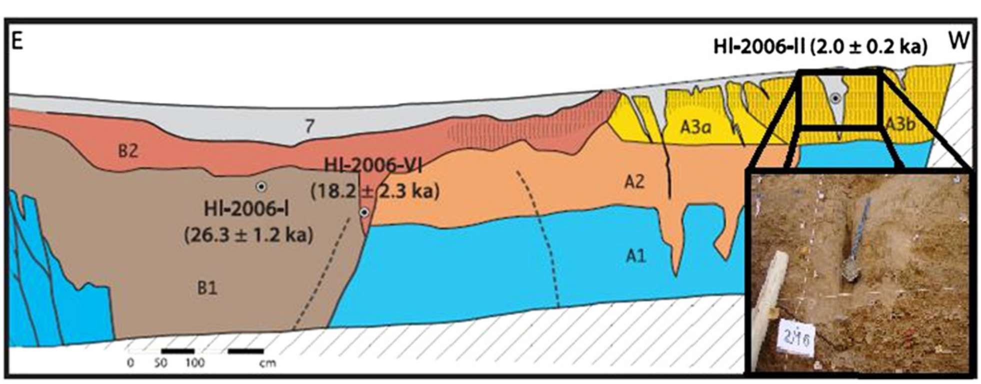


**Fig. 2.** Western part of the Gerdab trench logs on the Dehshir fault with the position and the dates of the OSL samples. Sedimentary units are indicated by different colours and labelled numerically. Units A and B are young alluvial and colluvial units. Unit 7 denotes the sandy silty unit infilling open fissures and mantling the ground surface after occurrence of the last surface rupturing earthquake. Inset shows where Hi2006II sample was collected.

scenario). All subsequently measured apparent values of $D_e$ were less than 0.5 Gy for preheat temperatures from 160 °C to 300 °C. This is small compared with typical natural $D_e$ and suggests that the samples do not suffer from significant thermal transfer.

### 4.3. Dose recovery preheat plateaus

Dose recovery preheat tests (as per Murray and Wintle, 2003) were carried out to provide a method to determine whether the overall effects of sensitivity changes had been properly corrected for and test whether known laboratory doses can be recovered by the modified SAR protocol. Three aliquots were used for each preheat temperature. After depleting the natural signal by light (OSL at room temperature for 200 s), each aliquot was given (~11.6 and 96.5 Gy for samples Hi2006II and Hi2006VI, respectively) beta doses and this dose was measured using the SAR protocol. The results are shown in Fig. 3 together with recycling ratios.

Thermal treatments (conventionally called preheat) are needed to empty any light sensitive unstable/shallow traps, particularly those filled by laboratory irradiations. Thermal treatments are a function of heating rate, the temperature to which the preheating is conducted to and the time at which the sample is held at this temperature. To determine the appropriate thermal treatments in the SAR protocol, two different heating rates (2 and 5 °C/s) were tested for preheat temperature ranges from 160 to 260 °C on sample Hi2006II. This sample showed no apparently constant $D_e$ in the temperature interval 180–260 °C for heating rate 5 °C/s. The given dose could not be recovered to within 20% and the relevant recycling ratios were not close to unity (Fig. 3a). In contrast, the same sample with a heating rate of 2 °C/s greatly improved the ability to both recover a given dose and in terms of recycling meeting the SAR requirements (0.93, 1.0 and 1.05 for three aliquots, respectively) especially for temperatures below 220 °C (Fig. 3b). Recuperation was also noted to be smaller. The requirement of a slower heating rate was confirmed with results from sample Hi2006VI (Fig. 3c). As a result a preheat temperature of 200 °C or 220 °C with a heating rate of 2 °C/s was used for samples Hi2006II and Hi2006VI respectively for $D_e$ determination.

## 5. $D_e$ determination and age calculation

Up to forty-eight 9.6 mm diameter aliquots for each sample were prepared and measured using the optimised SAR protocol. Following measurement of the naturally acquired dose, a dose–response curve was constructed from five dose points including three regenerative doses (8, 16 and 26 Gy), and a zero dose (Fig. 4). A replicate measurement of the lowest regenerative dose was carried out at the end of each SAR cycle. The first 2 s of OSL decay curve was used for signal, and the final 10 s of OSL decay curve was used as a background for all measurements. The result of aliquots that created no significant recuperation signals and produced recycling ratios between 0.90 and 1.10 was chosen for further $D_e$ analysis and age determination. These quality control criteria resulted in the rejection of 54%, 21% and 12% of aliquots for samples Hi2006I, Hi2006II and Hi2006VI, respectively. Results from the replicate $D_e$ measurements for these samples can be seen in Table 1 and Fig. 5. From this it is apparent that Hi2006I has both a low over-dispersion (OD; a calculation of the level of $D_e$ variability in a data set which exceeds that which would be expected from a well-bleached sample) of 8% and low level of skewing (0.58). In contrast sample Hi2006VI has an OD value of 21% and sample Hi2006II shows a high OD value (47%). Both show skewing with a hint of a low $D_e$ shoulders and some high $D_e$ outliers (Table 1, Fig. 5d & f). Whilst not as convincingly skewed as reported for poorly bleached samples elsewhere (e.g. Rodnight et al., 2005; Olley et al., 1999),

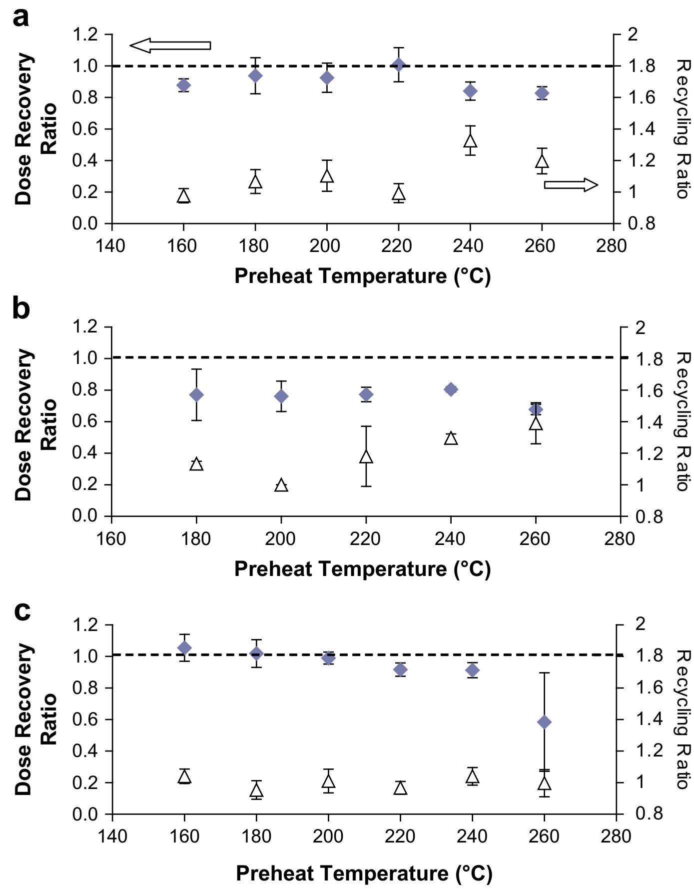


**Fig. 3.** Recycling ratio (open triangles) and preheat plateau for dose recovery test (solid diamonds) using different preheat temperatures and heating rates. (a) Heating rate of 2 °C/s for sample Hi2006II; (b) heating rate of 5 °C/s for sample Hi2006II and (c) heating rate of 2 °C/s for sample Hi2006VI. Note: dashed line denotes the given laboratory dose.

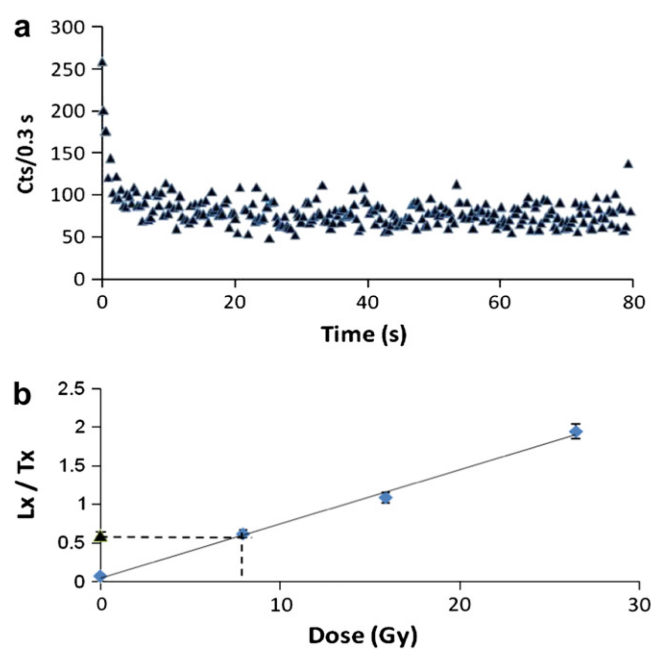


**Fig. 4.** An example of the OSL decay and SAR growth curve for sample Hi2006II showing (a) the weak natural OSL signal and (b) despite this, a good SAR growth curve could be measured.

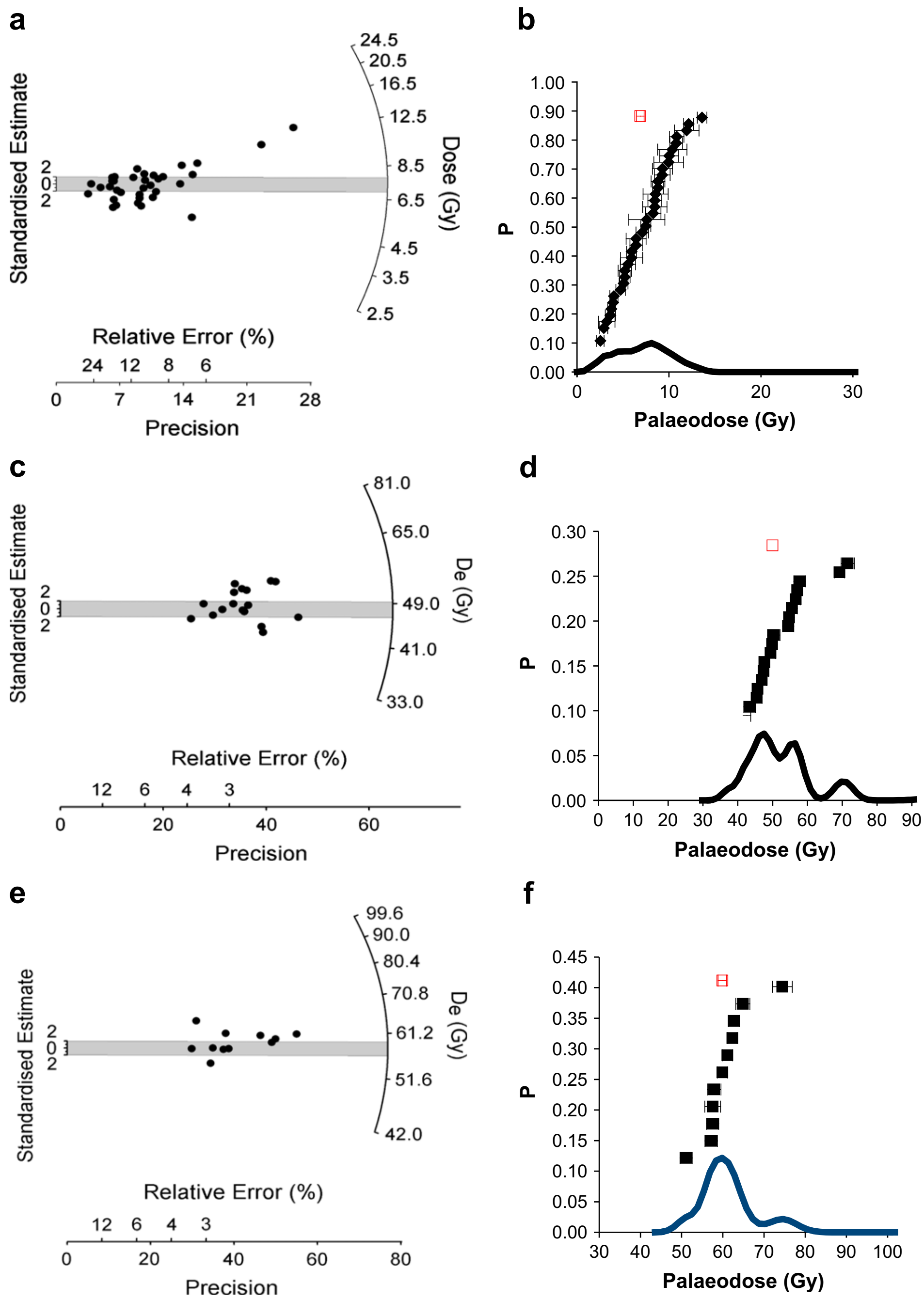


**Fig. 5.** $D_e$ distributions for samples Hi2006II (a, b), Hi2006VI (c, d) and Hi2006I (e, f). Showing radial plots on the left and probability ($P$) density plots on the right with individual aliquot $D_e$ plotted above (closed square) and the arithmetic mean of the data (open square).

given the depositional setting and the $D_e$ distributions shown in Fig. 5, there is likelihood that the samples were incompletely bleached prior to deposition. As measurements are at the multi-grain level with an unknown number of grains contributing to OSL signal from each aliquot, multiple $D_e$ populations within a sample (particularly ones with lower $D_e$ values) may be largely masked (e.g. Bateman et al., 2003, 2008). Thus, slight low $D_e$ shoulders on distributions when plotted as a combined probability plot may be significant as an indicator of partial bleaching problems. If this is the case then basing age calculations on an assumption that all the data were from a single population (as done in Nazari et al., submitted for publication), would lead to an over-estimation of true burial age and high uncertainties. In response to these concerns, we have excluded aliquot data which fell outside 2 standard deviations of the mean as statistical outliers and then have applied different statistical approaches in order to calculate a suitable single $D_e$ value for age determinations. By calculating the OD and skewness of the data it was possible to apply the Bailey and Arnold (2006) decision making test to determine which statistical model might best be used to minimize the inclusion of partially bleached data. This recommended the adoption of the Central Age Model (CAM; Galbraith et al., 1999) from which was derived a $D_e$ value of $60.24 \pm 0.28$ Gy, $6.79 \pm 0.08$ Gy and $48.78 \pm 0.33$ Gy for samples Hi2006I, Hi2006II and Hi2006VI, respectively. For comparison, data

**Table 1**
Dose rates, equivalent dose and calculated ages for quartz (size range between 90 and 250 μm) from the 3 samples. CAM and FMM are the Central Age Model and the Finite Mixture Model, respectively.

| Sample | Lab code | Depth (m) | U (ppm) | Th (ppm) | K (%) | Cosmic (Gy/ka) | Dose rate (Gy/ka)[c] | $N$[a] | Over-dispersion | Skewness | CAM $D_e$ (Gy) | FMM $D_e$ (Gy) | $P$[b] | CAM age (kyr) | FMM age (kyr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hi2006II | Shfd07043 | 0.45 | 1.67 | 5.5 | 0.73 | 0.24 | $1.79 \pm 0.06$ | 38 | 47% | 1.56 | $6.79 \pm 0.08$ | $3.63 \pm 0.28$ | 19 | $3.8 \pm 0.1$ | $2.0 \pm 0.2$ |
| Hi2006VI | Shfd07044 | 1.5 | 2.04 | 6 | 1.27 | 0.21 | $2.43 \pm 0.09$ | 21 | 21% | 1.52 | $48.78 \pm 0.33$ | $48.84 \pm 1.22$ | 86 | $20.2 \pm 0.8$ | $20.2 \pm 0.9$ |
| Hi2006I | Shfd07042 | 1.2 | 1.79 | 6 | 1.22 | 0.22 | $2.29 \pm 0.09$ | 11 | 8% | 0.58 | $60.24 \pm 0.28$ | | | $26.0 \pm 1.0$ | – |

[a] $N$ is the number of aliquots out of the 24 (48 for Hi2006II) not rejected using the quality control parameters and falling within two standard deviations of the mean $D_e$.
[b] $P$ is percent of the data which fell in the lowest $D_e$ cluster.
[c] A standard palaeomoisture content of 1.1% was applied to all samples.

were also analysed with the Finite Mixture Model (FMM; Galbraith and Green, 1990) with a sigma $b$ of 0.1 and a $k$ value between 4 and 2 (dependant of which minimized Bayesian information criterion or BIC in the model; see Galbraith and Green, 1990). Results from data for sample Hi2006II showed that 19% of the data fell in $D_e$ cluster around $3.6 \pm 0.3$ Gy, 25% of the data had a $D_e$ cluster of $5.7 \pm 0.5$ Gy and 44% of the data had a $D_e$ value of $9.4 \pm 0.5$ Gy, and 12% of data had a $D_e$ cluster of $15.5 \pm 1.2$ Gy. For sample Hi2006VI, 86% of the data fell in $D_e$ cluster around $48.8 \pm 1.2$ Gy and 14% of data had a $D_e$ cluster of $79.5 \pm 5.0$ Gy. Finite mixture modelling was not necessary for sample Hi2006I as this, after the outlier removal, had a normal distribution with only a single mode (Table 1).

As sample Hi2006II is from the stratigraphically youngest sediment, it must have a true burial $D_e$ less than the minimum $D_e$ measured for samples Hi2006VI (min $= 37.4 \pm 1.3$ Gy), assuming similar dose rates for the samples. Both statistical approaches appear to meet this requirement, however, using the lowest $D_e$ identified by FMM (assuming this has the highest proportion of well-bleached grains) a much younger age is calculated for sample Hi2006II. This sample has a CAM age of $3.8 \pm 0.1$ kyr compared to an FMM age of $2.0 \pm 0.2$ kyr. Application of FMM to sample Hi2006VI makes little difference to the final age as it has a CAM age of $20.2 \pm 0.8$ kyr compared to an FMM age of $20.2 \pm 0.9$ kyr. Using FMM for samples Hi2006II and Hi2006VI and CAM for sample Hi2006I to calculate ages it can be seen that ages increase in antiquity with depth and that they confirm to stratigraphy so that sample Hi2006II, relating to the most recent movement on the fault, gives the youngest age. The age of Hi2006VI might correspond to the penultimate event provided that the sedimentation record is complete.

Irrespective of which statistical approach is adopted, the OSL results show that the last fault movement has definitely occurred within the Late Holocene. However, in the absence of any independent age control, it is not possible to be absolutely sure which of the statistical approaches undertaken to derive a single $D_e$ for age calculation, gives the most accurate burial age for this fault related sample. The high level of OD and skewing of the sample would suggest that some partially bleach material has been incorporated within the single aliquot measurements. Thus, whilst both statistical approaches reduce uncertainties when compared to the work of Nazari et al. (submitted for publication), using the $D_e$ derived from CAM to calculate an age would probably lead to an overestimate of the true burial age for sample Hi2006II. Based on the FMM derived $D_e$, the last earthquake which caused fault movement, occurred around $2.0 \pm 0.2$ kyr. The age of sample Hi2006VI might correspond to a previous earthquake event at around $20.2 \pm 0.9$ kyr.

## 6. Conclusions

Applying OSL for dating quartz extracted from colluvial samples from Iran is usually difficult and time consuming. The samples used for this study suffered from weak OSL signal and initially a lack of a preheat plateau even for dose recovery tests. The performance of the SAR protocol was improved by experimentally determining an appropriate test dose and adjusting both the preheat temperature and the ramp-time. Despite this, for $D_e$ determination many aliquots per samples had to be rejected as they did not satisfy the quality control SAR requirements. As the depositional context had a high probability of inclusion of partially bleached sediment, an understanding of the $D_e$ distributions of mixed dose populations at the aliquot level was needed. Accordingly, whilst CAM was suggested on the basis of samples' $D_e$ distributions and skewness, FMM was preferred as the most likely to minimize the impact of age overestimation due to partial bleaching. Ages calculated for this study therefore show that the most recent earthquake causing slippage in the Dheshir fault appears to be around $2.0 \pm 0.2$ kyr. This refines considerably the age window of 1.4–4.2 kyr reported by Nazari et al. (submitted for publication) in which the last earthquake could have taken place. It also demonstrates that the historical record of earthquakes may be incomplete for the Iranian antiquity, because an $M \geq 6.5$ event is not mentioned in the region located around the Deshir fault. This result is critical for seismic hazard assessment and strengthens the urgent need for thorough palaeoseismic investigations in Central and Eastern Iran.

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