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Research paper

# Luminescence dating of the last earthquake of the Sabzevar thrust fault, NE Iran

Morteza Fattahi[a,b,*], Richard T. Walker[c]

[a]The Institute of Geophysics, University of Tehran, Kargar Shomali, Tehran, Iran
[b]OLRG, School of Geography, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
[c]COMET, Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK

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**Abstract**

Iran is one of the world's most tectonically active regions, yet dating past earthquakes for neotectonic studies has been limited. One of the main reasons for this is that organic material suitable for radiocarbon dating of deformed sediments is rare. We investigate the use of infrared stimulated luminescence (IRSL) from coarse-grained feldspars to date colluvial deposits associated with the Sabzevar thrust fault in northeastern Iran. The single-aliquot regenerative (SAR) dose measurement procedure was used for this study. The current study investigates monitoring and correcting for sensitivity changes, recovering a known laboratory dose and equivalent dose estimation using three SAR IRSL methods. It is shown that SAR has recovered a given laboratory dose using a range of preheat temperatures but $D_e$ determination of natural samples requires its own preheat plateaus for two of these SAR methods. The SAR IRSL method provided an age of 1.7 ± 0.3 ka for colluvium, predating the last earthquake event on the Sabzevar fault. This result suggests that this fault is likely to be responsible for an earthquake that destroyed Sabzevar city in AD 1052.

*Keywords:* Luminescence dating; Fault slip-rate; Iran; Earthquake; Seismic hazard

## 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. For example, an earthquake on the 26th December 2003, with a moment magnitude (Mw) of 6.5, resulted in the loss of over 30,000 lives and almost totally reduced the ancient city of Bam and surrounding villages to ruins (e.g., Talebian et al., 2004).

The city of Sabzevar in NE Iran has been relatively free from earthquakes in the modern age, although slight damage was caused by two small earthquakes (with magnitudes of 4.6 and 4.2), on the 12th and 17th December 2004 (from, Institute of Geophysics, Tehran University). However, Sabzevar remains at risk from earthquakes in the future, and historical sources describe how the city was destroyed by a large earthquake in AD 1052 (named the Baihaq earthquake; Ambraseys and Melville, 1982). As the Sabzevar thrust is the major identifiable active fault in the region, and passes very close to the city (Fig. S1), it seems likely that this fault was responsible for the AD 1052 event. However, as surface ruptures were not recorded at the time (Ambraseys and Melville, 1982), this link remains to some extent conjectural.

## 2. Sampling site and experimental treatment

Following each earthquake on a thrust fault in which slip reaches the Earth's surface, surficial processes modify and gradually degrade the fault scarp, by eroding material from the (uplifted) hanging-wall side of the fault, and depositing this sediment on the (downthrown) footwall side of the fault, forming a wedge of colluvial sediment. An exposure through the Sabzevar fault scarp at 36:13:18N 57:31:33E

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*Corresponding author. OLRG, School of Geography, University of Oxford, South Parks Road, Oxford OX1 3QY, UK.
Tel.: +44 01865 556407; fax: +98 21 8009560, +44 1865 275885.
*E-mail addresses:* morteza.fattahi@ouce.ox.ac.uk, m.fattahi@ut.ac.ir (M. Fattahi).

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revealed a colluvial wedge, presumably relating to several earthquake events. The uppermost layer of colluvium was clearly cut by faulting (Fig. S2), suggesting that the most recent earthquake post-dates the exposed colluvium. The age of these colluvial sediments therefore provide a valuable constraint on the maximum age of the last faulting event on the Sabzevar fault. The likely interval between large earthquakes on the Sabzevar fault, and hence the local earthquake hazard, can be estimated by combining our results with estimates of the average fault slip-rate (Fattahi et al., 2006).

One sample (sample S6) was collected from the uppermost layer of colluvium. The infrared stimulated luminescence (IRSL) signal of this sample should be completely reset if deposition of this post faulting sediment has been sufficiently slow. Previous studies have shown that the rapidly bleached IRSL signal in alkali feldspars (e.g., Hutt et al., 1988) is reset during colluvial depositional processes (e.g., Porat et al., 1996).

The modified single-aliquot regenerative (SAR) dose protocol of quartz (Murray and Wintle, 2000) was applied to aliquots of 90–150 μm feldspar, which were prepared by wet sieving, HCL and $H_2O_2$ treatment, followed by heavy liquid separation ($<2.58\,\mathrm{g/cm^{-3}}$). All the experiments reported here were carried out using a Risø automated TL/OSL system (Model TL/OSL-DA-15; fitted with a $^{90}\mathrm{Sr}/^{90}\mathrm{Y}$ beta source delivering $\sim 5\,\mathrm{Gy\,min^{-1}}$) equipped with an IR laser diode ($\lambda = 830\,\mathrm{nm}$) as stimulation source. The intensity of light incident on the sample was about $400\,\mathrm{mW\,cm^{-2}}$. IRSL was detected using a electron tubes bialkaline PMT. Luminescence was measured through 7 mm Hoya U-340 filters.

## 3. Luminescence dating/characteristics

Murray and Wintle (2000) introduced the SAR dose protocol for quartz which uses the luminescence signal from a test dose administrated after the regeneration dose luminescence measurement to monitor, and then correct for, any sample sensitivity changes during the measurement process. Several workers tried to extend the SAR protocol to coarse-grain feldspar and to recover known laboratory doses and estimate the $D_e$ value. Some have reported that SAR can successfully recover a known laboratory dose (e.g., Fattahi, 2001; Fattahi and Stokes, 2004; Preusser, 2003; Blair et al., 2005). Others have found an underestimation of the known laboratory dose (e.g., Wallinga et al., 2000a,b). However, these studies have used different preheat, cut heat and stimulation temperature.

This work focuses on the testing of assumptions for three different SAR procedures (Table 1). The first procedure employs a cut heat at 220 °C and stimulation temperature at 50 °C (e.g., Wallinga et al., 2000a,b) The second one applies a cut heat at 220 °C and stimulation temperature at 125 °C (e.g., Preusser, 2003). The third method uses equal preheat and cut heat with IR measuring temperature at 150 °C (e.g., Fattahi, 2001; Blair et al., 2005).

### 3.1. Sensitivity changes and corrections

Sensitivity changes were checked by repeated (7 times) cycles in SAR procedure with a repeated fixed regeneration and test dose. The fundamental assumption in SAR protocol is that if a plot of regeneration dose IRSL ($L_x$) vs. test dose IRSL ($T_x$) shows a straight line that passes through the origin, the sensitivity-correction procedure has worked properly (Murray and Wintle, 2000).

The above procedure was applied to check the validity of a test dose to monitor and correct the sensitivity changes using three different heating methods. The regeneration dose and test dose were 2.0 and 1.2 Gy, respectively. All IRSL measurements were for 100 s. The preheat temperatures were 200, 230, 250, 270 and 290 °C for the three procedures. Three aliquots were used for each measurement. The results of the average of the three aliquots for each measurement are shown for three methods in Fig. 1. For preheat temperature up to 270 °C, in the method in which preheat and cut heat are equal, the linear relationship passes through the origin (Fig. 1c). For two other methods (when the cut heat and preheat temperature are not equal in both time and temperature) there is no linear relationship which passes through the origin and $L_x$ and $T_x$

Table 1
Generalized single-aliquot regenerated sequence and outline of the steps involved in the three different SAR methods

| Step | Treatment 1 | Treatment 2 | Treatment 3 | Ob.[a] |
|---|---|---|---|---|
| 1 | Give dose | Give dose | Give dose | – |
| 2 | Pre-heat (210–290 °C) | Pre-heat (210–290 °C) | Pre-heat (210–290 °C) | – |
| 3 | Stimulation (at 50 °C) | Stimulation (at 125 °C) | Stimulation (at 150 °C) | $L_x$ |
| 4 | Give test dose | Give test dose | Give test dose | – |
| 5 | Cut heat (220 °C) | Cut heat (220 °C) | Cut heat = Preheat | – |
| 6 | Stimulation (at 50 °C) | Stimulation (at 50 °C) | Stimulation (at 50 °C) | $T_x$ |
| 7 | Return to 1 | Return to 1 | Return to 1 | – |

*Note*: In step 2, the sample has been heated to the pre-heat temperature using TL and held at that temperature for 10 s.

[a] Observed: $L_x$ and $T_x$ are derived from the initial IRSL signal (5 s) minus a background estimated from the last part of the stimulation curve. Corrected natural signal $N = L_0/T_0$; Corrected regenerated signal $R_x = L_x/T_x$ ($x = 1-5$).

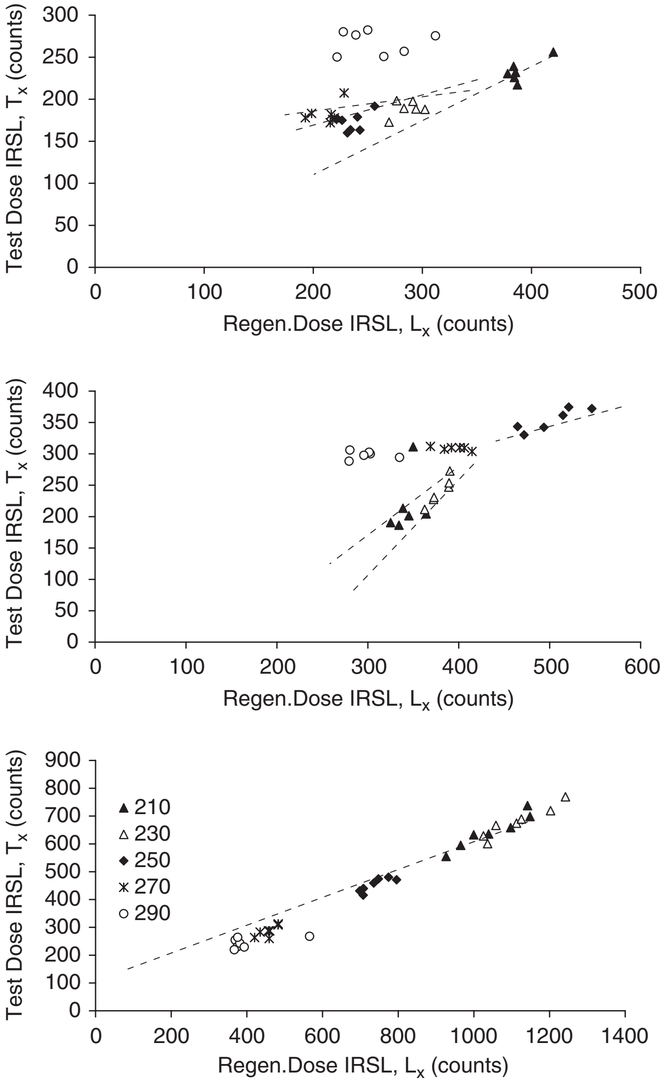
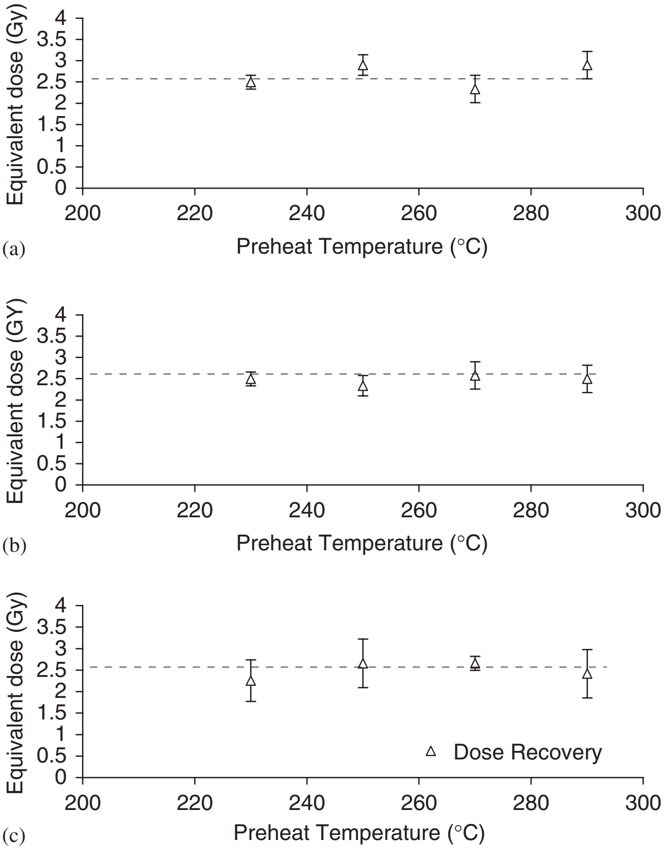


Fig. 1. Sensitivity correction tests using different preheating temperature shown in the figures. (a) The cut heat was fixed at 220 and sample temperature was 50 °C. (b) The cut heat was fixed at 220 and sample temperature was 125 °C. (c) The cut heat was equal to preheat and sample temperature was 150 °C. The dashed lines are the trend lines.

are not correlated after 250 °C preheat temperature (Fig. 1a, b). There is a one-to-one relationship between $L_x$ and $T_x$ up to 250 °C for the second method (IRSL temperature at 125 °C).

### 3.2. *Thermal transfer and dose recovery tests*

To test thermal transfer of charge into the IRSL trap as a result of preheating (e.g., Rhodes, 2000) the natural aliquots were stimulated twice at room temperature and IRSL was measured for 100 s, with more than 4 h delay between stimulations (to empty the rapidly bleaching trap). No IRSL signal was observed for the second measurement. This suggests that thermal transfer is not a likely source of uncertainty in these aliquots.



(a)

(b)

(c)

Fig. 2. Dose recovery test. (a) The cut heat was fixed at 220 °C and sample temperature was 50 °C. (b) The cut heat was fixed at 220 °C and sample temperature was 125 °C. (c) The cut heat was equal to preheat and sample temperature was 150 °C. The dashed lines are presented to show the dose to be recovered.

Dose recovery tests were carried out to provide a method to determine whether the overall effects of sensitivity changes had been properly corrected for. Three aliquots were used for each preheat temperature. After depleting the natural signal, each aliquot was given ~2.6 Gy beta doses and this dose was measured using the three above mentioned SAR procedures (Table 1) and results are shown in Fig. 2. Although all three methods have successfully recovered the laboratory dose, the accuracy of the second method is the best.

### 3.3. *$D_e$ determination and dating*

The equivalent dose ($D_e$) preheat plateau (Fig. 3) was obtained using the three single-aliquot regeneration methods (Table 1). The preheat time used for all measurements (210–290 °C) was for 10 s. IRSL was measured for 100 s for three methods at 50, 125 and 150 °C sample temperature, respectively.

Three disks were prepared for each preheat temperature and following measuring the natural dose, a dose–response curve was constructed from five dose points including three regenerative doses (1.5, 2 and 4 Gy), and a zero dose. A replicate measurement of the lowest regenerative dose

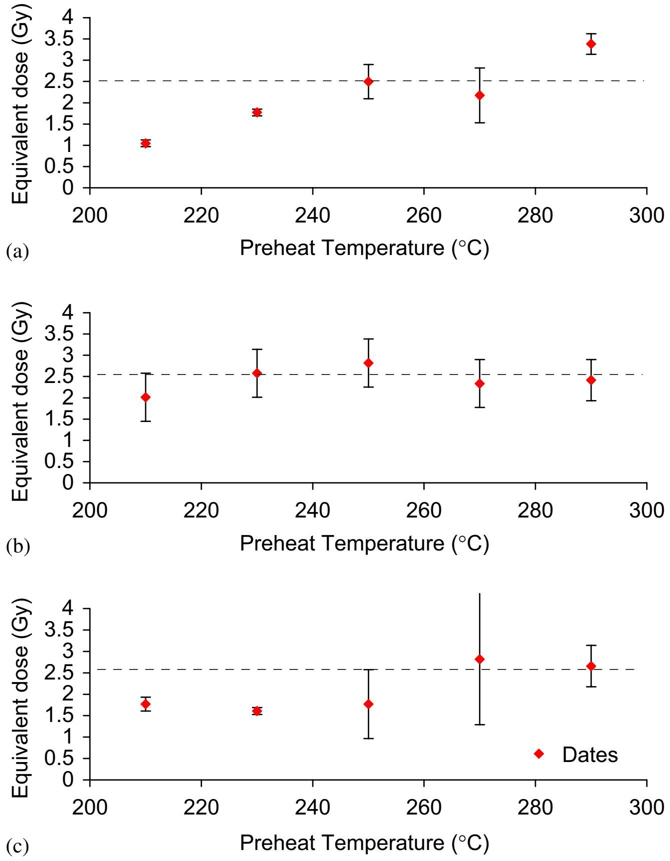


Fig. 3. Plot of equivalent dose as a function of preheat temperature. (a) The cut heat was fixed at 220 °C and sample temperature was 50 °C. (b) The cut heat was fixed at 220 °C and sample temperature was 125 °C. (c) The cut heat was equal to preheat and sample temperature was 150 °C. The dashed lines are presented to show the accepted value of $D_e$ (2.54 ± 0.08 Gy) for age determination. The scattering of $D_e$ measured for each preheat temperature is shown by large variability in the error bars.

was carried out at the end of each SAR cycle. The net initial IRSL signal (first 5 s—average of 90–100 s) was used for natural, regenerated and test dose measurements. The $D_e$ was determined by interpolation and the sensitivity was corrected by dividing $L_x$ by $T_x$. No aliquot produced significant recuperation signals and all produced recycling ratio between 0.90 and 1.10. The dose recovery test suggested the second SAR method as the most accurate method (Fig. 2b). There is also a clear plateau in the second method for $D_e$ values (mean $D_e = 2.54 \pm 0.2$ Gy) in the preheat temperature range of 230–290 °C. Therefore, we used this mean value for age determination.

### 3.4. Anomalous fading test

A fading test was performed by repeated (7 times) cycles of the SAR procedure with a fixed regeneration (2.6 Gy) and test dose (1.2 Gy) at five different preheat temperatures (three aliquots for each preheat temperature). After four cycles all aliquots were stored in the oven at 100 °C, following exposing to 2.6 Gy dose. After 3 weeks storage, the regeneration signal and response to the test dose (1.2 Gy) was measured (fifth cycle). Then two more cycles of the SAR procedure with a fixed regeneration (2.6 Gy) and test dose (1.2 Gy) was repeated.

The results are shown in Fig. 4. The average of these measurements at different preheat temperature shows a drop at cycle number 5. The fading ratio was calculated by the ratio of sensitivity corrected IRSL of the stored dose ($L_5/T_5$) divided by the average of sensitivity corrected IRSL before storage ($L_4/T_4$) and the ratio of prompt measurement after storage ($L_6/T_6$). This suggests that the sample suffers from 10% fading (Fig. 4).

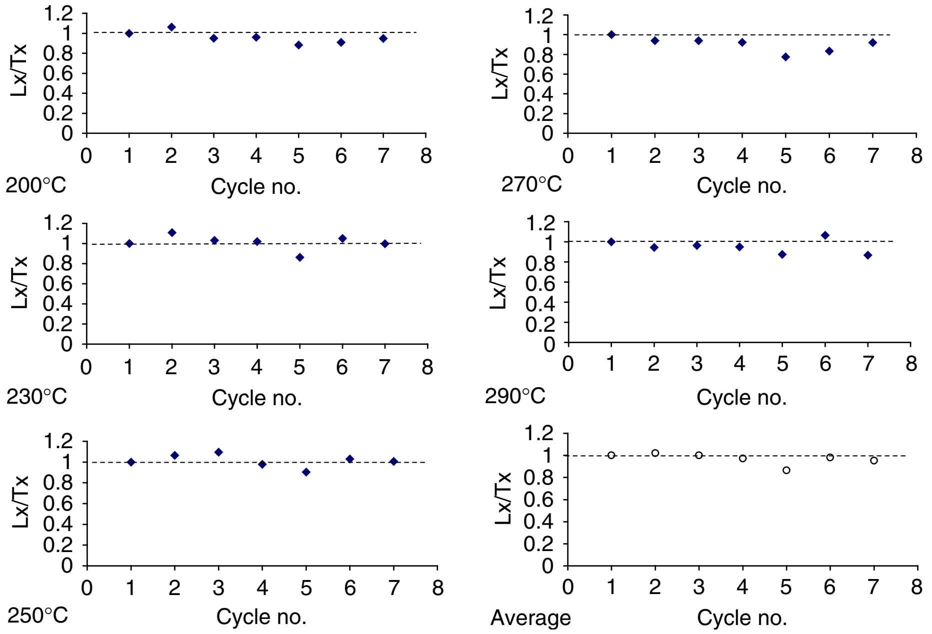


Fig. 4. Fading test: sensitivity corrected IRSL signal as a function of repeated cycles using different preheating temperature shown in the figures. The bottom right is the average of 15 aliquots for each cycle.

Table 2
Values used to calculate luminescence ages from Sabzevar fault, NE Iran

| Sample | Grain (μm) | Water (%) | Depth (m) | K (%) | U (ppm) | Th (ppm) | Cosmic (Gy/ka) | $D_{\text{int}}$ (mGy/yr) | $D_{\text{Ext}}$ (mGy/yr) | Dose rate (mGy/yr) | $D_e$[a] (Gy) | Age[b] (ka) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S6 | 90–150 | 2.5 | 1.5 | 0.852±0.051 | 0.871±0.050 | 2.779±0.160 | 0.0147±0.000 | 0.44±0.04 | 1.14±0.04 | 1.58±0.20 | 2.8±0.3 | 1.77±0.29 |

[a] After fading correction.

[b] Uranium, thorium and potassium concentrations were measured using field gamma spectrometry. Present-day moisture contents were determined by drying at 40 °C in the laboratory. The conversion factors for water contents of Aitken (1985) were used for the calculation of alpha, beta and gamma dose rates. Alpha and beta dose rates were corrected for attenuation due to grain size using the factors of Bell (1980) and Mejdahl (1979).

## 4. Discussion and conclusions

The linear relationship between $L_x$ and $T_x$ which passes through the origin in third method (Table 1, Fig. 1c) satisfies the basic requirement of SAR method. For two other methods an increasing or decreasing intercept (in comparison to zero) can be interpreted that $L_x$ and $T_x$ show different sensitivity changes (Fig. 1a, b).

All methods recovered the known laboratory dose in all preheat temperature examined within their estimated error and the best result was obtained by the second method (Fig. 2b). However, surprisingly only the second method has shown a preheat plateau for the natural $D_e$ (Fig. 3b). The first method has shown a rising trend of $D_e$ with increasing preheat temperature (Fig. 3a). Some one may suggest that the rising trend can be the result of thermal transfer. Preheating can result in thermal transfer from shallow traps to the traps sampled during OSL measurement. Unwanted thermal transfer can occur in nature if the light-insensitive traps are thermally unstable, and part of their charge is re-trapped in the OSL trap. Such thermal transfer can cause an overestimation of age and cannot be avoided by using a low preheat. However, there is no evidence that this sample is suffering from thermal transfer. The third method has shown two preheat plateau. One plateau is shown at around 1.85 Gy between 210 and 250 °C and the other at around 2.54 Gy between 270 and 290 °C.

However, based on dose recovery test and a clear plateau in the second method for $D_e$ values (mean $D_e = 2.54 \pm 0.2$ Gy) in the preheat temperature range of 230–290 °C, we used this mean value for age determination.

The result of fading tests showed that the feldspar grains are subject to anomalous fading (~10%) and as such, have provided an apparent deposition age which is younger than the real age. If we consider a natural fading of ~10% then the $D_e$ can increase to ~2.80 Gy and the age can increase to $1.7 \pm 0.3$ ka.

Table 2 shows the values used to determine sample age and the derived age estimate. External dose was measured by a portable gamma spectrometer and for calculation of internal K dose rate, potassium contents of $12.5 \pm 0.5\%$ were used (see Preusser, 2003).

The IRSL age of feldspar grains therefore indicates that the colluvial sediments are young, and that the faulting that cuts them must date from less than ~1800 years ago. Given this age range, it is likely that the faulting observed in Fig. S2 does represent surface deformation from the AD 1052. Baihaq earthquake, which is therefore likely to have occurred on the Sabzevar fault.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quageo.2006.06.006.

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