Quaternary Science Reviews 30 (2011) 1256–1271

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# A framework of Holocene and Late Pleistocene environmental change in eastern Iran inferred from the dating of periods of alluvial fan abandonment, river terracing, and lake deposition

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ARTICLE INFO

*Article history:*
Received 20 November 2010
Received in revised form
3 March 2011
Accepted 4 March 2011
Available online 12 April 201112 April 2011

*Keywords:*
Iran
Asia
Holocene
Landscape evolution
Palaeoenvironment

ABSTRACT

We review studies of the Holocene and Late Pleistocene stratigraphy of eastern Iran to infer past changes in the environment within this presently arid region. We build a scenario of widespread, and presumably climatically driven, evolution of the landscape through the Holocene. Six sites, covering a 10° range in latitude, indicate a regional abandonment of alluvial fan surfaces at ∼10 ± 3 ka, with the younger (∼9 ka) end of this age range supported by several of the best-constrained studies. Incision of rivers into the fan surfaces has occurred in discrete stages in the early to mid-Holocene (∼9–7 ka) leading to the formation of flights of river terraces. Detailed records of lakebed deposition in the presently arid interior of Iran are rare, though the available data indicate lake highstand conditions at <7.8 ka at South Golbaf in SE Iran and at < 8.7 ± 1.1 ka at the Nimbluk plain in NE Iran. The major periods of Holocene landscape development hence correlate with a period of time where water was more abundant than at present, with incision of rivers into thick alluvial deposits possibly occurring due to a combination of decreased sediment supply and high levels of precipitation, and with the formation of inset river terraces possibly responding to century-scale fluctuations in precipitation. No major geomorphic changes are identified within the later part of the Holocene, from which we infer that increased aridity has slowed evolution of the landscape. A decrease in precipitation in the mid-Holocene may have had a detrimental effect on bronze age societies in eastern Iran as has been inferred elsewhere in the eastern Mediterranean region. The pre-Holocene environmental changes in eastern Iran are less well constrained, though there are suggestions of alluvial fan abandonment at 40–60 ka, at ∼80 ka, and at ∼120 ka.


## 1. Introduction

The last few tens of thousands of years are recognised as a period of extreme, and sometimes rapid, changes in environment that have had a profound effect on the evolution of landscapes and the development of complex human societies (e.g. deMenocal, 2001). Our paper focuses on the desert interior of eastern Iran (Fig. 1), which is amongst the hottest and most arid regions on Earth at present (e.g. Mildrexler et al., 2006). The harsh environment of today may not, however, be representative of the late Quaternary period as a whole. In particular, the presence of large alluvial fans, whose surfaces are now abandoned and incised by deep river canyons, indicate that profound changes to the landscape have occurred in the geologically recent past (e.g. Giessner et al., 1984; Fattahi et al., 2007; Meyer and Le Dortz, 2007; Shabanian et al., 2009; Hollingsworth et al., 2010). Until now, however, there has been little in the way of constraint on the timing of periods of landscape development, their relationship to changes in regional environment, and their impact on the people living in the region.

The development and subsequent abandonment of the mountain range-front alluvial fans in eastern Iran may record regional changes in the environment, as is seen in other parts of the world (e.g. Pratt et al., 2002; Poisson and Avouac, 2004; Owen et al., 2006). However, as the region is undergoing active tectonic deformation, many of the large mountain ranges of eastern and central Iran are bounded by active faults and the cycles of aggradation and dissection recorded in the landscape might, instead, be responding to local changes in base-level caused by tectonic movements (e.g. Regard et al., 2006). The comparison of quantitative age data from

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doi:10.1016/j.quascirev.2011.03.004

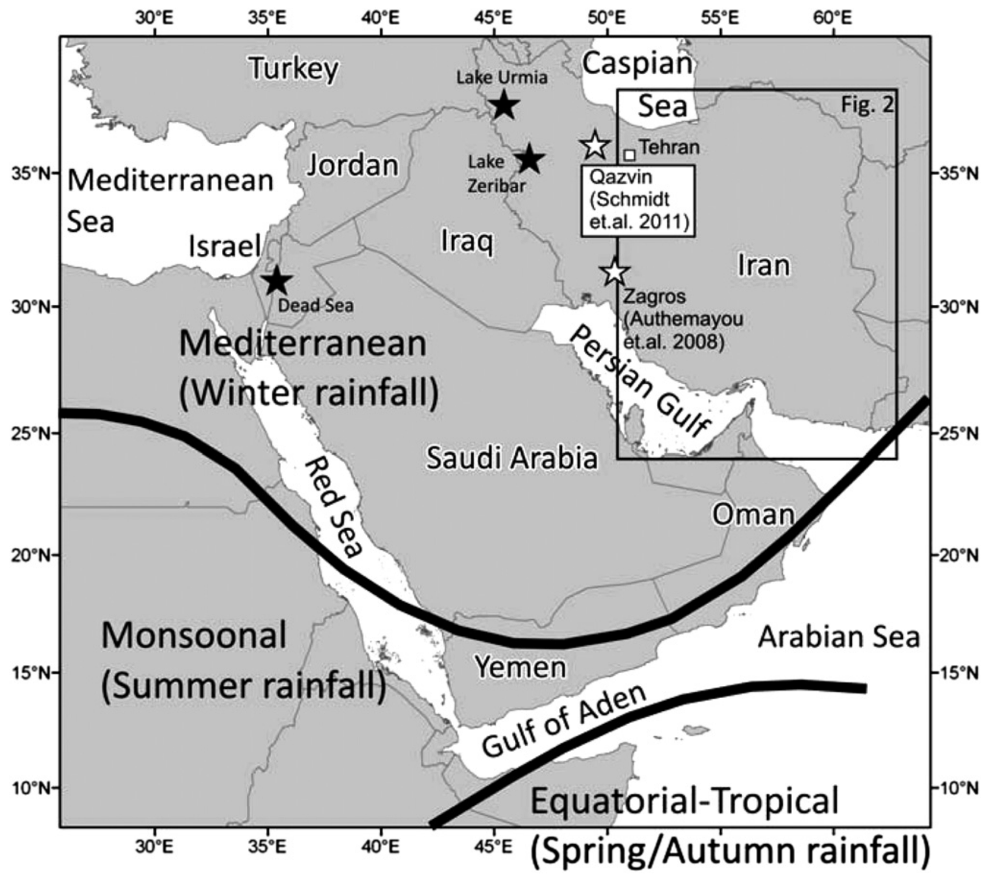


**Fig. 1.** Map of Iran and surrounding parts of the eastern Mediterranean and Middle East. Locations referred to in the text are labelled. The boundaries between the main climate regimes of the present day are delineated by thick black lines (from Gasse, 2000; Arz et al., 2003).

numerous, widely spaced, sites is therefore required to distinguish between the localised landscape evolution caused by base-level changes of tectonic origin, and the regional patterns caused by changes in the environment (e.g. Owen et al., 2006).

Increasing aridity and periods of prolonged drought in the mid- and late Holocene have been cited as the cause of collapse in a number of agricultural civilisations from Mesopotamia, North Africa, and the Indus valley (e.g deMenocal, 2001; Staubwasser and Weiss, 2006). It is possible that changes in environment would also have exerted an influence on the development of early farming societies within the desert regions of eastern Iran. A record of the environmental changes that have occurred through the Holocene of eastern Iran is of use, therefore, to studies of societal development in the mid-Holocene of this region, which so far lack detailed constraints on the environments under which civilisations developed and declined (e.g. Potts, 2003; Adle, 2006; Fouache et al, 2008).

There is an additional societal motivation for unravelling the history of landscape evolution in eastern Iran. Determining whether the cycles of range-front alluvial fan deposition and incision are synchronous across large areas, and are hence representing regional variations in the environment rather than local changes at the catchment scale, has large implications for understanding the hazard posed by active faults to local populations. Iran is one of the most tectonically active parts of the continents, with widespread occurrence of destructive earthquake events (e.g. Ambraseys and Melville, 1982; Berberian and Yeats, 1999), and the arid environment causes human populations to be concentrated along the edges of mountain ranges, where water is less scarce, but where the risk from earthquakes is highest (e.g. Jackson, 2006). If the periods of alluvial fan deposition and incision correlate over large regions, and if the amount by which the abandoned fan surfaces have been displaced by active faults is measured, an assumption of their ages can be utilised to make rapid assessments of fault slip-rate across wide areas. Determining the slip-rate of an active fault is a valuable constraint both in understanding the local earthquake hazard and the regional tectonics. An example of this approach is given by Meyer and Le Dortz (2007) who use an assumed abandonment age of $\sim$10 ka for the youngest generation of fans, combined with measurements of displacement of the fan surfaces derived from satellite imagery, to estimate the average rate of slip on many of the main active faults across the region.

Constraining the timing and controls on late Quaternary landscape development in the deserts of Iran is of use, therefore, in the study of past environmental change, in informing us of the hazard posed by earthquakes, and in aiding our understanding of the development of ancient societies. Unravelling the record of past changes in landscape will also be a useful constraint in studies of past and future changes in climate (e.g. Jones et al., 2011). In this paper, we review several studies of late Quaternary alluvial fan, river terrace, and lakebed deposits, spanning a 10° range in latitude, to show that the timing of landscape development appears to be synchronous across eastern Iran. We then examine the possible palaeo-environmental and, more speculatively, palaeoclimatic scenarios that could account for the observed chronology of late Quaternary deposits.

## 2. Dating methods

The existing sites span ~10° of latitude from the southeast to the northeast of Iran (Fig. 2). The initial motivation of each of the dating studies that we describe has been to quantify the average rate of slip, and hence the average interval between destructive earthquakes, on active faults that have displaced the abandoned surfaces of the fans (e.g. Regard et al., 2005; Fattahi et al., 2006; Le Dortz et al., 2009). Because of this, the primary criterion in site selection has been in finding places where the alluvial fan surfaces have been displaced by an unambiguous amount across the active faults, and the exposures and sediments encountered at the sample sites are often far from ideal for the application of Quaternary dating methods. Limitations in the precision of the dating methods in the types of sediment found in the study regions mean that the periods of major change in the landscape have not typically been determined with uncertainties less than a thousand years.

Organic remains for radiocarbon dating are rare in the arid desert interior of Iran. The majority of studies that we summarise have therefore used cosmogenic nuclide exposure dating or luminescence dating: either optically-stimulated luminescence (OSL) dating of Quartz grains or Infrared-stimulated luminescence (IRSL) of Feldspar. Luminescence techniques require an assumption that the sediments had sufficient exposure to sunlight during deposition for any luminescence signal acquired during previous burial events to be dissipated. If this assumption is not valid, the age calculated from the $D_e$ will overestimate the real deposition age, and luminescence measurements from single grains are therefore usually preferred to the more traditional multiple-aliquot and single-aliquot methods when dealing with alluvial and fluvial environments such as those often encountered in Iran (e.g. Duller, 2008). Unfortunately, the luminescence responses from sediments encountered in eastern Iran are typically dim, with many grains showing little or no accumulated signal (e.g. Fattahi et al., 2009), such that single-grain analyses are typically not viable.

In the following sections we describe the types of sediment available for sampling, the methods employed, and the major sources of uncertainty at each site. A brief description of each site, along with the age data and uncertainties, is tabulated in Table 1.

## 3. Holocene changes in river and lake hydrology in eastern Iran

### 3.1. Timing of alluvial fan abandonment

#### 3.1.1. Sabzevar

The northernmost of the existing sites is situated close to the city of Sabzevar at 36°13′N (Fattahi et al., 2006; Fattahi and Walker, 2007; Fig. 2) where a number of southward-flowing drainage systems, originating in Kuh-e-Siah to the north, have led to the deposition of several generations of alluvial fan deposits (Fig. 3a–b). The surfaces of these alluvial fans have been displaced vertically across the Sabzevar thrust fault by amounts that can be

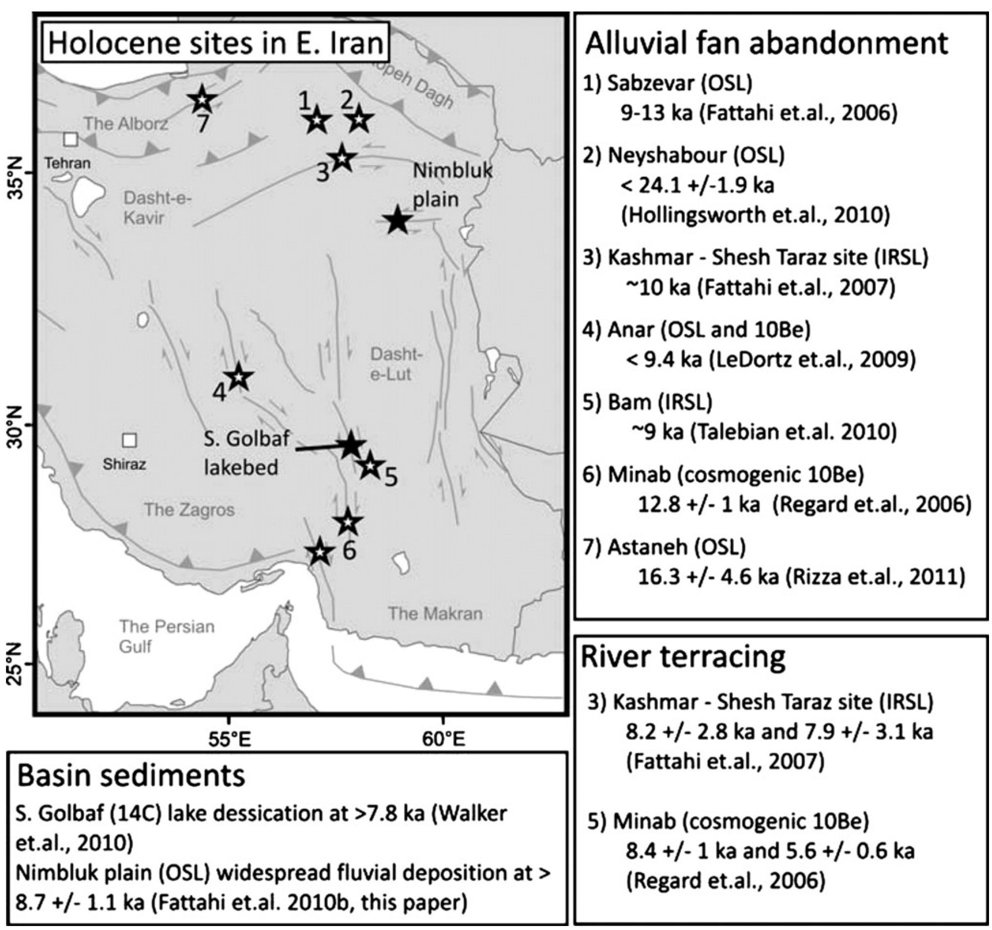


**Fig. 2.** Map of eastern Iran showing sites at which landforms of Holocene age have been dated. The numbered white stars refer to sites where the youngest widespread generation of alluvial fans have been dated. Sites 3 and 6 also constrain the timing of fluvial incision by dating periods of river terracing. Black stars mark the location of dated basin deposits at South Golbaf and the Nimbluk plain. Active faults are from Walker et al. (2010). The adjacent tables list the relevant age data, along with the dating methods used (OSL - Optically-stimulated luminescence; IRSL - Infra-red stimulated luminescence; 10Be - cosmogenic $^{10}$Be exposure dating).

**Table 1**
Summary of all available age constraints on periods of Holocene fan abandonment (HFA), Holocene river terracing (HRT), Holocene basin deposition (HLD), Pleistocene fan abandonment (PFA), and Pleistocene carbonate formation (PCF) reviewed in this paper. Age constraints from studies outside our core area (i.e. those described briefly in Section 3.1.7) are not listed in this table. Age data that does not constrain periods of landscape change are also not included (for instance, at sites where a number of samples were taken through the stratigraphy, only the uppermost sample is listed). A star in the method column indicates that in-situ dose measurements were made with a portable gamma-spectrometer. Further details of the individual sites and age data are given in the relevant sections of the text.

| Site name | Location | Method | Target | Material | Age | Ref | Section |
|---|---|---|---|---|---|---|---|
| Sabzevar | 36°13.323′N<br>57°31.552′E | OSL* | HFA | Coarse alluvium + fine-grained sand | Between 13 ± 0.7 and 9 ± 1 ka | Fattahi et al., 2006 | 3.1.1 |
| Neyshabour | 36°18.335′N<br>58°50.280′E | OSL*<br>(minimum De age) | HFA | Sand unit within alluvium | 24.1 ± 1.9 ka | Hollingsworth et al., 2010 | 3.1.2 |
| Kashmar (Shesh Taraz) | 35°17.805′N<br>58°09.769′E | IRSL<br>(samples from two nearby pits) | HFA | Coarse alluvium | 10.6 ± 1.3 ka<br>9.9 ± 4.6 ka | Fattahi et al., 2007 | 3.1.3 |
| Anar | 31°11.993′N<br>55°09.137′E | OSL<br>(samples from two nearby sites) | HFA | Silt units within alluvium | 11.8 ± 6.5 ka<br>5.8 ± 3.6 ka | Le Dortz et al., 2009 | 3.1.4 |
| Bam | 29°00.717′N<br>58°23.983′E | IRSL | HFA | Silt horizons within alluvium | 9.2 ± 1.5 ka | Talebian et al., 2010 | 3.1.5 |
| Minab | ~27.50°N<br>~57.25°E<br>(various sites) | 10Be | HFA | Surface boulders | 12.8 ± 1.0 ka | Regard et al., 2006 | 3.1.6 |
| Minab | ~27.50°N<br>~57.25°E<br>(various sites) | 10Be | HRT<br>(2 generations) | Surface boulders | 1) 8.4 ± 1.0 ka<br>2) 5.6 ± 0.6 ka | Regard et al., 2006 | 3.2 |
| Kashmar (Shesh Taraz) | 35°17.805′N<br>58°09.769′E | IRSL | HRT<br>(2 generations) | Coarse gravel | 1) 18.2 ± 2.8 ka<br>2) 7.9 ± 3.1 ka | Fattahi et al., 2007 | 3.2 |
| South Golbaf | 29°47.319′N<br>57°46.473′E | 14C | HBD | terrestrial wood in lake carbonates | 7.8 ± 0.1 ka | Walker et al., 2010 | 3.3 |
| Nimbluk basin | 34°02.048′N<br>58°50.042′E | OSL | HBD | fine-grained fluvial deposits | 8.7 ± 1.1 ka | Fattahi et al., 2010a | 3.3 |
| Minab | ~27.50°N<br>~57.25°E<br>(various sites) | 10Be | PFA<br>(two generations) | surface boulders | 1) 20.1 ± 1.5 ka<br>2) 44.0 ± 3.4 ka | Regard et al., 2006 | 5 |
| Kashmar (Uch Palang) | 35°16.962′N<br>58°34.390′E<br>(various sites) | IRSL<br>(samples from two nearby pits) | PFA | coarse alluvium | 48.0 ± 14.7 ka<br>51.4 ± 10.2 | Fattahi et al., 2007 | 5 |
| Neyshabour | ~36°17.7′N<br>~58°39.1′E<br>(various sites) | OSL* | PFA<br>(two generations) | sand layers within alluvium | 1) 35.4 ± 5.7 ka and 59.7 ± 10.3 ka<br>2) 82.3 ± 7.0 ka | Hollingsworth et al., 2010 | 5 |
| Kopeh Dagh | ~37°36.9′N<br>~58°04.3′E<br>(various sites) | 36Cl | PFA<br>(two generations) | limestone surface boulders | 1) 83 ± 4 ka<br>2) 280 ± 16 ka | Shabanian et al., 2009 | 5 |
| Sefidabeh | 30°58.305′N<br>60°31.679′E | U-series | PCF | calcite-cemented sand | 99 + 30/-24 ka | Parsons et al., 2006 | 5 |

measured in the field (e.g. Fattahi et al., 2006) or on digital topographic models (e.g. Hollingsworth et al., 2010).

The youngest generation of widespread mountain-front fan deposition, which is present adjacent to catchments along the length of the Sabzevar fault, has been displaced vertically across the Sabzevar thrust fault by ~10 m (Fattahi et al., 2006; Fig. 3c). An OSL sample from a depth of ~0.7 m below the surface of the alluvial fan yielded an age of 13 ± 0.7 ka. This sample was extracted from relatively coarse-grained alluvial sediments and as such should be treated as a maximum only. A minimum date for the fan abandonment was obtained from the infill of a small fault-bounded graben at the fault scarp. The infill of this graben, which clearly displaces the alluvial surface, is of red-coloured sand that postdates the deposition of coarse-grained alluvial deposits. OSL dating of the fine-grained sediments at the base of the infill yielded an age of 9 ± 1 ka. These two OSL samples hence bracket the surface abandonment age between 13 ± 0.7 ka and 9 ± 1 ka.

In addition to bracketing the fan abandonment age, Fattahi et al. (2006), suggest that the alluvial deposition had continued uninterrupted since 32 ± 3 ka based on an OSL date of the lowest exposed alluvial sediments at the site (Fig. 3b). This age should be treated as a maximum value only as it was measured from coarse-grained sediments that might not have been fully reset during transport.

### 3.1.2. Neyshabour

Hollingsworth et al. (2010) provide a constraint on the age of the most recent period of alluvial fan deposition at a site close to the city of Neyshabour at latitude 36°18′N (Fig. 2). Approximately 25 m of alluvial gravels are exposed in a deep river cutting. The surface of the alluvial fan, and the alluvial sediments exposed in the river cutting, are displaced vertically by ~8 m across the North Neyshabour Thrust.

A thick sand unit, at a depth of ~20 m from the fan surface, was found within the otherwise uniform sequence of coarse alluvial gravels. A single OSL sample was extracted from the sand layer. The full spread of OSL data, which are extremely scattered, yield a mean age of 55.0 ± 21.3 ka. Rather than using the mean age, which is likely to incorporate the effects of partially bleached sediment grains (see Section 2), Hollingsworth et al. (2010) instead calculate an age of 24.1 ± 1.9 ka from the aliquot showing minimum $D_e$ that they consider more likely to approximate the real deposition age.

Although the single OSL sample at Neyshabour is insufficient to provide a date for the abandonment of the alluvial fan, it does show that abandonment is likely to postdate 24.1 ± 1.9 ka. As the minimum De age of 24.1 ± 1.9 ka from the Neyshabour sample is consistent with the 32 ± 3 ka onset of alluvial deposition estimated at Sabzevar (Fattahi et al., 2006; Section 3.1.1) it seems plausible that, as at Sabzevar, the deposition of alluvial gravels at the Neyshabour site ended at ~10 ka.

### 3.1.3. Kashmar (the Shesh Taraz river)

Fattahi et al. (2007), provide an IRSL age of 10.6 ± 1.3 ka for sediments buried ~0.6 m beneath the surface of a large alluvial fan near the town of Kashmar (latitude 35°18′N; Fig. 2). The fan surface

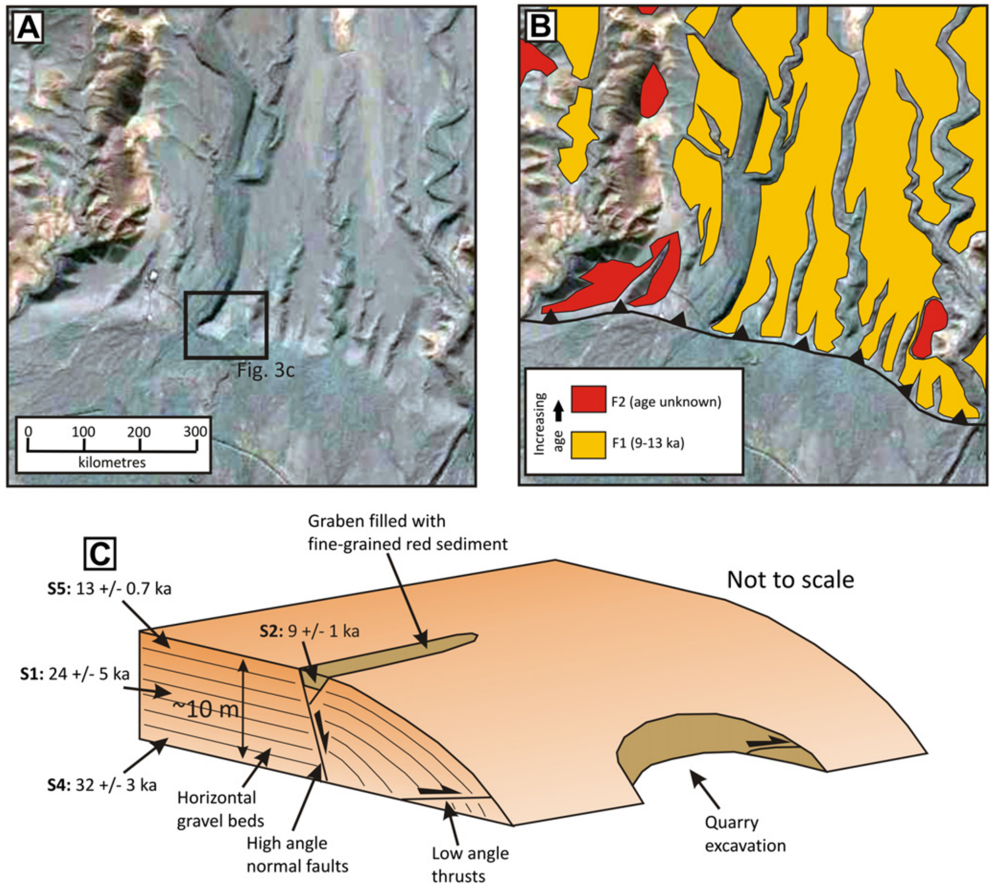


**Fig. 3.** (a) SPOT5 satellite image (from Googleearth) showing the scarp of the Sabzevar reverse fault in northeast Iran (see Fig. 2 for location). The scarp is developed in the surface of alluvial fans deposited along the southern margin of Kuh-e-Siah. The underlying Neogene bedrock (coloured pink in the image) is exposed in some places. (b) Geomorphic map showing two successive generations of abandoned alluvial fans F1 and F2. The two fan generations are separated vertically by continued uplift of the region north of the active Sabzevar reverse fault. The periods of fan deposition are punctuated by periods of river incision and fan surface abandonment (e.g. Fattahi et al., 2006). (c) Block diagram showing the 9.5 m-high scarp of the Sabzevar thrust fault in young alluvial fan deposits derived from the adjacent Siah Kuh mountains. Optical dating of quartz grains in samples S4, S1 and S5 indicate alluvial deposition from 32 ± 3 ka through to 13 ± 0.1 ka. The fan surface must have been abandoned prior to deposition of the aeolian sediments dated at 9 ± 1 ka (sample S2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

has been abandoned, and is now incised by the Shesh Taraz river (Fig. 4). Sediments deposited with the levee of a channel on the fan surface, which should have the same deposition ages as the fan abandonment age, were dated at 9.9 ± 4.6 ka (the average from two separate size fractions). We note that the sand grains used in the experiment were extracted from coarse alluvium; introducing uncertainty in whether the luminescence signal in the sediment grains was reset during transport and deposition. Dose rates were calculated in the laboratory from ICP-MS measurements of U, Th and $^{40}$K, which, given the inhomogeneous nature of the sediments, introduces an additional source of uncertainty. However, as all three measurements provide mean ages of ~9–10 ka, Fattahi et al. (2007), suggest that a fan abandonment age of ~10 ka is likely to be correct.

### 3.1.4. Anar

Le Dortz et al. (2009) use both $^{10}$Be exposure dating and OSL dating to determine the abandonment age of two alluvial fans deposited by rivers flowing westwards from Kuh-e-Bafq (at latitudes 35°12′N and 35°16′N; Fig. 2). The alluvial fan surfaces are displaced by ~8m by the right-lateral Anar fault. The river cuttings expose a sequence of coarse alluvial gravels with rare silt lenses. Le Dortz et al. (2009) found that OSL dates of silt lenses within the top ~1 m of the fan deposits yielded ages in the early Holocene (11.8 ± 6.5 ka and 5.8 ± 3.6 ka) from which they estimate a fan abandonment age within the early Holocene (at a maximum age of 9.4 ka).

Le Dortz et al. (2009) combined their OSL ages with cosmogenic $^{10}$Be exposure ages obtained from quartz-rich cobbles at the surface and from a depth profile through the alluvial sediments. The $^{10}$Be exposure ages from the two sites showed a large amount of scatter, with pebbles from the abandoned fan surface yielding exposure ages that range from 18 ± 1.1 ka to 77.8 ± 4.9 ka. This scatter is interpreted to represent variable amounts of inherited 10Be originating from a complex history of bedrock exhumation and transport that varies between clasts. In support of this interpretation, pebbles extracted from the modern river-bed also show large amounts of inheritance with exposure ages of 6.2 ka to 18.4 ka. The large inherited signal effectively precludes their use in constraining the abandonment age of the fan surface.

### 3.1.5. Bam

Fattahi et al. (2010a) and Talebian et al. (2010) obtained OSL ages of ~9 ka from alluvial sediments, originating from the Jebal Barez mountains, at the town of Bam (latitude 29°00′N, Fig. 2) and now exposed in the uplifted hanging-wall of the Baravat fault escarpment (Fig. 5a; e.g. Jackson et al., 2006). Three samples were collected from a vertical exposure of alluvial gravels with dose rates calculated from in-situ gamma-spectrometry (Fig. 5b). The samples indicate that 1.85 m thickness of coarse-grained alluvial gravels

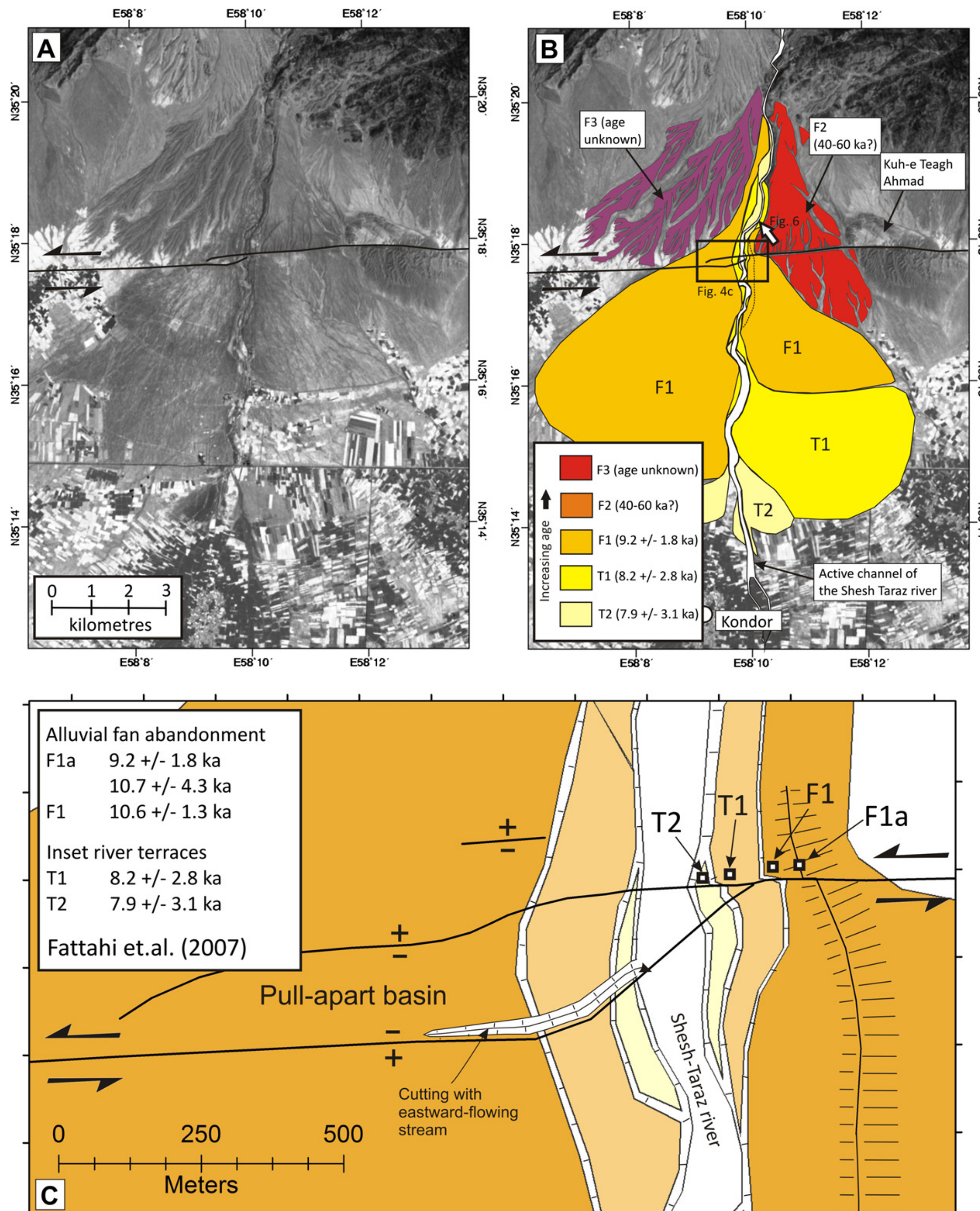


**Fig. 4.** (a) ASTER satellite image of the Shesh Taraz river. The river flows southwards from Kuh-e-Sorkh towards the internally-drained Kavir-e-Namak (south of the region shown). Three main phases of mountain-front alluvial fan deposition are observed. Successive generations of fan deposition are separated by periods of fluvial incision. (b) Interpretation of the ASTER image showing the three fan generations (F1, F2 and F3). The surface of the most recent alluvial surface F1 has been incised by the Shesh Taraz river leaving two main river terraces (T1 and T2) preserved in the channel margins. (c) Geomorphic map showing the F1 alluvial fan surface and two inset strath terraces (T1 and T2) where they are displaced across the Doruneh strike-slip fault. IRSL sampling locations are shown by white squares and the dating results are given in the inset box. The F1-T1 riser and a levee (F1a) riding on the F1 fan surface are displaced left-laterally by ∼25 m yielding an average slip-rate of ∼2.5 mm/yr on the Doruneh fault.

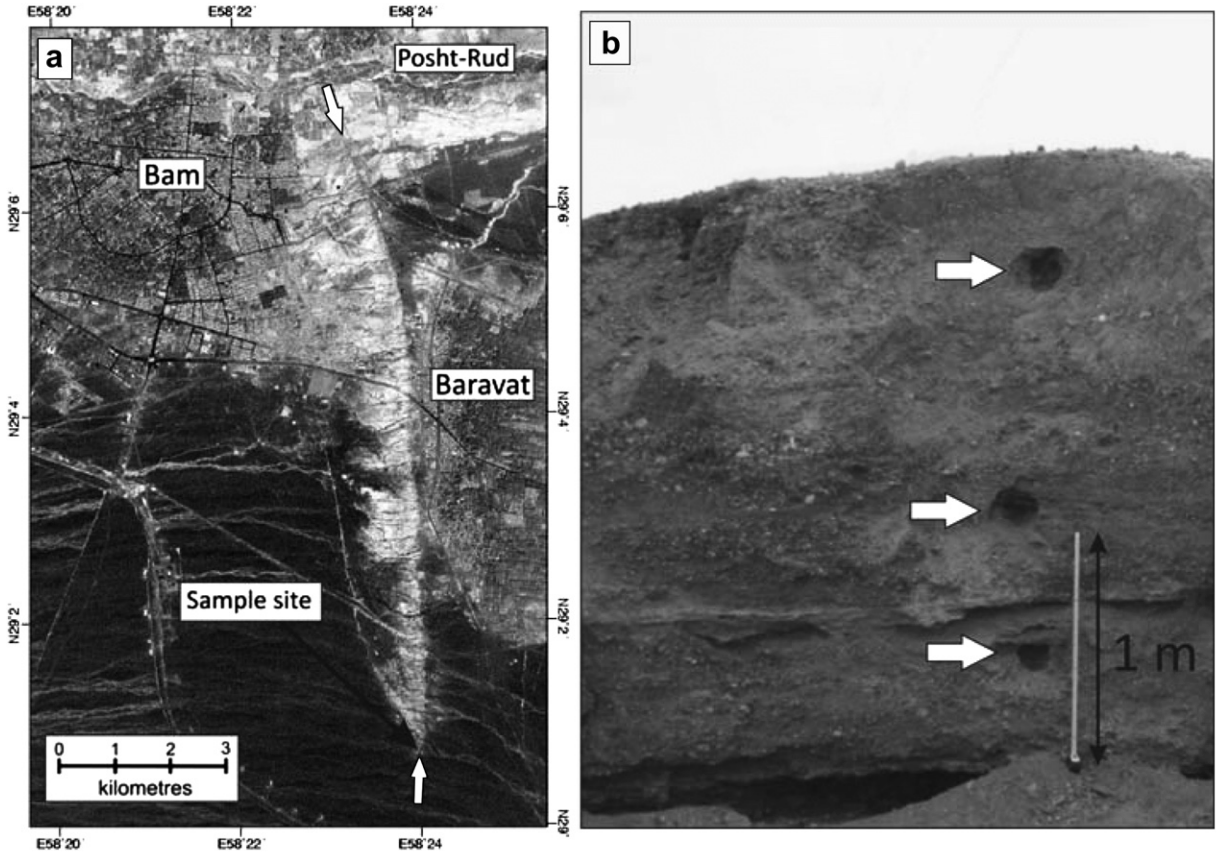


**Fig. 5.** (a) LANDSAT satellite image of Bam (Fig. 2) and the north-south Baravat fault escarpment (running between the two white arrows). Uplift west of the escarpment has caused the surface of a wide alluvial fan to be incised by streams. The black arrow marks a section through the alluvial fan sediments, which was sampled for IRSL dating. The Posht-Rud river flows eastwards across the northern edge of the image. (b) Field photograph (adapted from Talebian et al., 2010) showing the section of alluvial fan sediments and the three sample locations (marked by white arrows). The uppermost sample yielded an IRSL age of 9.2 ± 1.5 ka and the lowermost sample yielded an age of 19.2 ± 1.8 ka. The middle sample provided an age of 11.1 ± 0.9 ka (Fattahi et al., 2010a; Talebian et al., 2010).

were deposited from ~20 ka until ~10 ka (Fattahi et al., 2010a; Fig. 8c). The alluvial fan surface was then abandoned and incised by streams.

### 3.1.6. Minab

The southernmost abandoned alluvial fan surfaces that have been dated in eastern Iran are from the Minab region (Fig. 2; Regard et al., 2006) from $^{10}$Be exposure ages obtained from boulders embedded in the fan surfaces. Regard et al. (2006) produced a chronology of five surface abandonments within the past ~50 ka. They dated three pre-Holocene terrace levels at 44.0 ± 3.4 ka, 20.1 ± 1.5 ka, and 12.8 ± 1.0 ka. They also identified two Holocene levels, inset into the older levels, at 8.4 ± 1.0 ka and 5.6 ± 0.6 ka (see Section 3.2).

The terrace chronology produced by Regard et al. (2006) at Minab is very detailed, with five surface abandonments identified within the past ~50 ka, but relies on assumptions of both negligible inherited $^{10}$Be and of negligible post-depositional erosion (e.g. Putkonen and Swanson, 2003; Brown et al., 2005). It is unclear whether these assumptions are valid. In addition, the ages of all five surfaces are derived from a dataset of only 23 samples, of which three were excluded from the analysis because of their apparently anomalous exposure ages, such that the full scatter from samples in each individual surface cannot be assessed (e.g. Putkonen and Swanson, 2003). We note that in the only other study of cosmogenic $^{10}$Be concentrations in young (<50 ka) alluvial deposits in Iran extremely variable - and sometimes very high - inherited signals were found that effectively preclude a definite assignment of age (Le Dortz et al., 2009, see Section 3.1.4.).

### 3.1.7. Sites elsewhere within Iran

A gap in fluvial deposition, lasting for much of the Holocene, is observed across wide parts of Iran with rivers instead incising throughout this period (Brookes, 1982). In two studies in the Zagros of SW Iran, the Kor river near Shiraz (Fig. 2) shows incision from ~10 ka (Kehl et al., 2009), and the Tang-e-Bulaghi plain of Fars province, southeast of Shiraz, showed accumulation of sediment from ~9–8 ka followed by river incision (Rigot, 2010). In one study from the interior of western Iran, luminescence dating of sediments buried at shallow depths within an alluvial fan south of Qazvin city by Schmidt et al. (in press) yields ages in the range 12.7 ± 3.2 ka. A sample from ~1.8 m depth in a second fan exposure yielded an age of 8.8 ± 2.8 ka. Samples from deeper in the same exposure yield ages of 14.5 ± 8.0 and 20.3 ± 5.1 ka, and a sample from the uppermost part of the deposit, which may postdate abandonment of the fan surface itself, is dated at 2.2 ± 1.6 ka. In a final example, Rizza et al. (in press), obtained a luminescence age of ~16 ka from young alluvial sediments at Astaneh in the eastern Alborz mountains (Fig. 2).

## 3.2. Periods of river terracing

Rivers often spectacularly incise the abandoned alluvial fans across eastern Iran. In the case of the largest catchments the

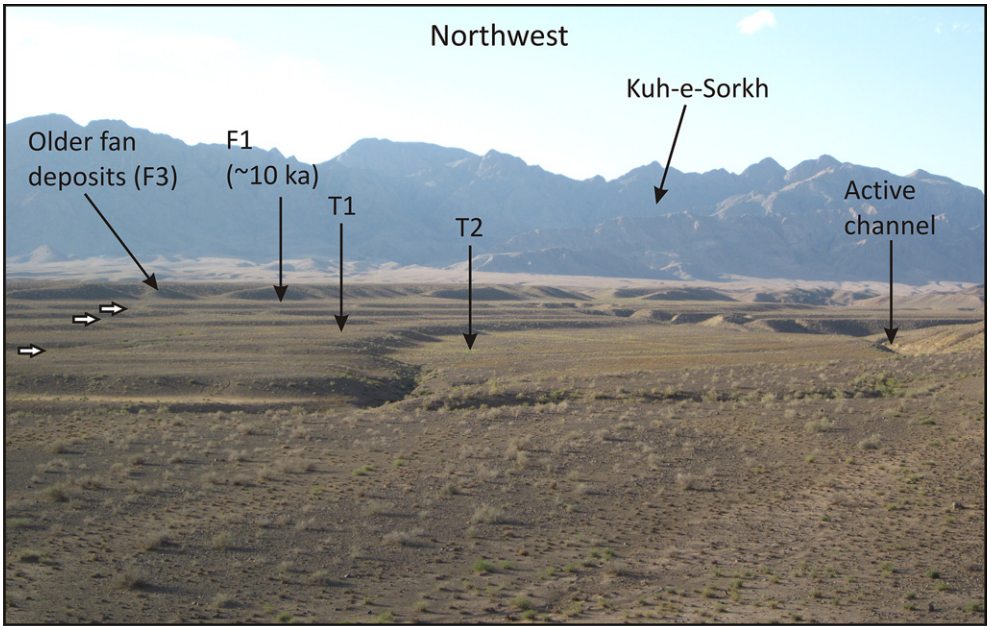


**Fig. 6.** Field photograph looking upstream and showing the six terraces of the Shesh Taraz ('Six levels') river near Kashmar (see Fig. 4a for photograph location). The active river channel, the two main Holocene terrace levels (T1 and T2), and the F1 alluvial fan surface are all visible. The risers of three additional terrace levels (not present in the area shown on Fig. 4), picked out in shadow, are marked by white arrows. Eroded alluvial fan deposits of pre-Holocene age (labelled F3 on Fig. 4b) are visible in the distance.

incision can be dramatic; with narrow canyons several tens of metres deep and prominent sequences of river terraces preserved in the channel margins. An example is the canyon of the Sardar river, near Tabas (e.g. Walker et al., 2003), which is up to 100 m deep in places.

Although the widespread river incision and terracing are well known, direct age constraints on the timing of their formation in eastern Iran are rare and there are only two studies that have attempted to provide ages on the sequences. One of these studies is sited at the Shesh Taraz river in northeast Iran and the other near Minab in the southeast of the country. In SE Iran, Regard et al. (2006) identify two Holocene levels, inset into their 12.8 $\pm$ 1.0 ka fan surface, and dated at 8.4 $\pm$ 1.0 ka and 5.6 $\pm$ 0.6 ka. Of these two inset levels, Regard et al. (2006) consider the $\sim$8.4 ka surface to reflect a local change in base-level and the $\sim$5.6 ka surface to be a response to regional change in the environment.

The Shesh Taraz ('Six levels') river in NE Iran, which flows southwards from Kuh-e-Sorkh, preserves a series of paired strath river terraces on its margins (Giessner et al., 1984; Fattahi et al., 2007). The terraces are cut into the surface of a large alluvial fan dated at 10.6 $\pm$ 1.3 ka (see Section 3.1.1) that is itself cut into an older generation of alluvial fan. Six terrace levels are visible close to the mountains (e.g. Fig. 6). The terraces merge downstream such that only two main inset terraces (T1 and T2) are distinguishable along most of the observed length of the river (e.g. Fig. 4c). Fattahi et al. (2007) provide feldspar IRSL ages of 8.2 $\pm$ 2.8 ka and 7.9 $\pm$ 3.1 ka from soil pits dug into the cover of T1 and T2 river terraces. Giessner et al. (1984) describe pottery fragments (of unknown age) within the fill of terrace T2 that presumably limits its deposition age to the Holocene. The paired river terraces each correlate with fan surfaces that indicate a progressive basinward migration of deposition throughout the early Holocene (Fig. 4).

### 3.3. *Timing of elevated lake levels*

The ability of a river to transport and deposit sediment varies with factors such as the rate of production of sediment within the source region, the binding of sediment by vegetation, as well as the amount of precipitation and river discharge (e.g. Schumm et al., 2002). Determining the actual palaeo-environmental changes that caused the transition from alluvial fan deposition, through incision by rivers, to eventually produce the landscape we see today thus requires independent constraints on the environmental history. In this section we describe indications of past changes in the availability of water provided by studies of lakebed deposition. We describe the one existing study of Holocene deposition of basin deposits in eastern Iran, at the South Golbaf palaeo-lake in southeast Iran (Walker et al., 2010; Fig. 7). We also document one additional constraint on basin sediment deposition in the Nimbluk valley at Dasht-e-Bayaz in the northeast (Fattahi et al., 2010b; Fig. 8). We then briefly compare the findings of these two studies to other lakebed records from around the eastern Mediterranean region.

The South Golbaf palaeo-lake is situated within a pull-apart basin along the Gowk right-lateral strike-slip fault (e.g. Walker and Jackson, 2002; Fig. 7). A build-up of alluvial deposits at the northern end of the South Golbaf depression has, at some point in the past, blocked the northward flow of drainage from the depression causing the drainage to instead pond in South Golbaf and form a lake. The waters of the lake subsequently rose, and eventually over-topped, the alluvial fan deposits. Drainage from the South Golbaf depression has then cut down through the alluvial deposits to re-establish a connection to the regional base-level of the Dasht-e-Lut. Walker et al. (2010) obtain radiocarbon ages of 7.9 and 7.8 ka for horizons at 1.8 m and 1.4 m depth within the lakebed deposits. As the South Golbaf desiccation at $\sim$7.8 ka indicates a time when the waters had risen to a level at which they were able to spill northwards and establish contact with through-going drainage (Walker et al., 2010), it predates any regional increase in aridity.

The low-relief surface of the Nimbluk plain in northeast Iran is underlain by widespread fine-grained fluvial sands and silts, which are locally exposed due to uplift along the Dasht-e-Bayaz strike-slip fault (e.g. Ambraseys and Tchalenko, 1969; Fig. 8). A single sample of fine-grained fluvial silt was collected from a depth of $\sim$1.25 m

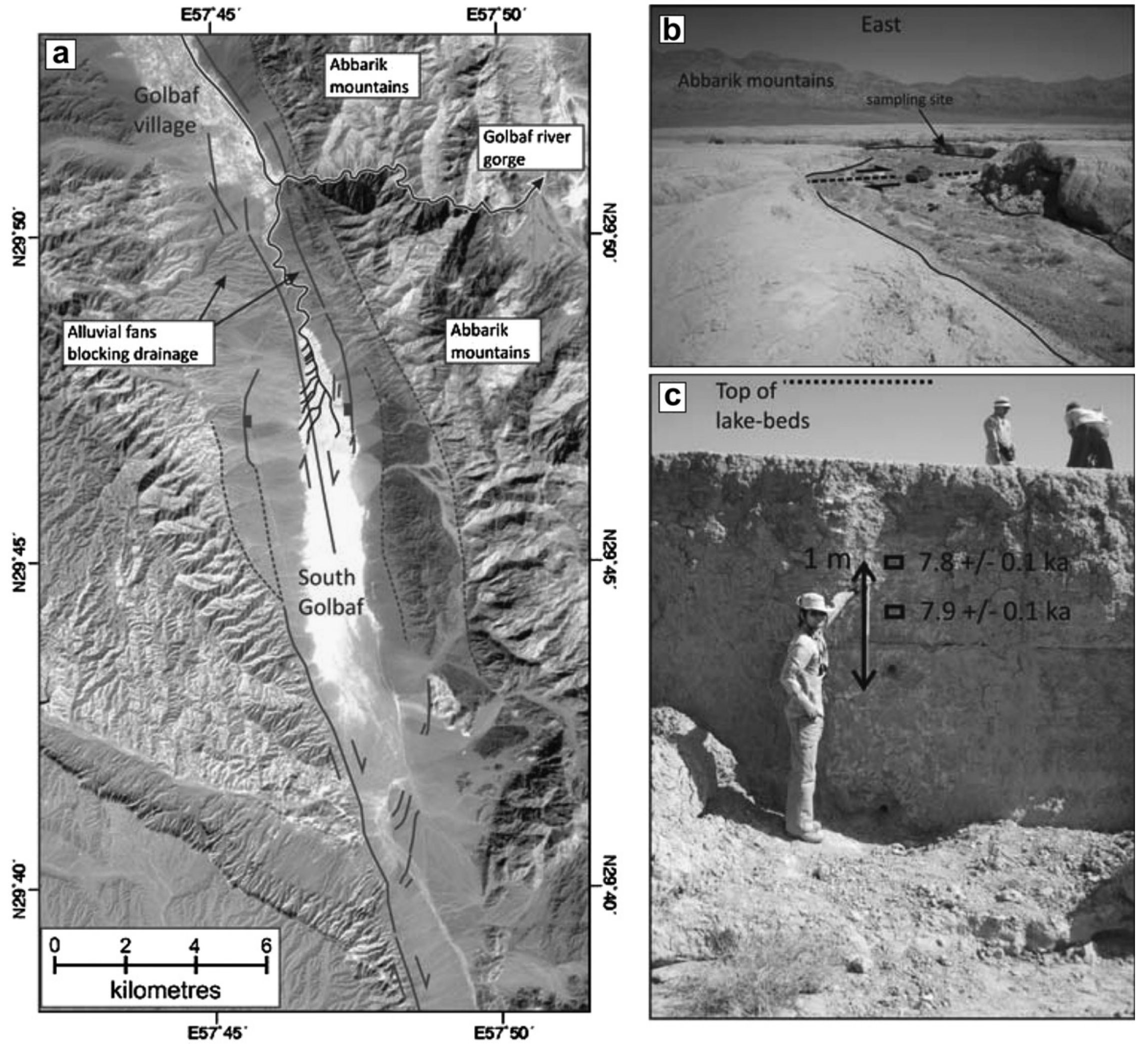


**Fig. 7.** (a) ASTER satellite imagery of the South Golbaf dry lakebed, which shows up as a white shades, and which is situated in a small basin between segments of the Gowk strike-slip fault. The South Golbaf basin was internally draining until rising lake waters were able to spill over the thick alluvial fan deposits that block the northern end of the basin. (b) Field photograph showing the sample location in the wall of a channel incised into the lakebed deposits. (c) Field photograph showing two wood fragments, exposed in a stream cutting through the lakebed deposits, which were radiocarbon dated by Walker et al. (2010). The lake highstand, at which time the lake dried out due to over-spilling, is dated to $< 7.8 \pm 0.1$ ka. Figure adapted from Walker et al. (2010).

within the sediments for dating with OSL (Fig. 8b; Fattahi et al., 2010b). Quartz grains in the 90–150 μm size range were isolated and dated following the preparation and analysis methods described in, for example, Fattahi et al. (2006). Dose rates were calculated from the values given in Table 2. A histogram of equivalent dose measurements from 22 aliquots is given in Fig. 8c. The tight clustering of equivalent dose measurements suggests that the assumption of complete solar resetting on deposition is valid in this case. The age calculated from the mean equivalent dose (Fig. 8c) and the calculated dose rate (Table 2) is $8.7 \pm 1.1$ ka. Although the Nimbluk sediments do not represent deposition within a lake, their age does show that the surface of the plain, which is now incised by a network of small streams, was formed by deposition of extensive fluvial sediments in the early Holocene.

A high moisture input in eastern Iran in the early Holocene is consistent with studies of lake deposition in other areas of the Middle East (Bar-Matthews et al., 1997, 2003). For instance, the Dead Sea experienced elevated lake levels in the early Holocene (Neev and Hall, 1979; Neev and Emery, 1995; Frumkin, 1997; Klinger et al., 2003), as did many other lakes in Africa and Arabia (Street and Grove, 1979; COHMAP members, 1988). The most detailed existing studies of lake cores in Iran, from lake Zeribar and the nearby lake Mirabad in the Zagros Mountains, and the lake Urmia record from the NW, are interpreted to show a climatic history that is somewhat different to elsewhere in western Asia. The cores show continued aridity in the early Holocene (e.g. Bottema, 1986; Snyder et al., 2001; Stevens et al., 2006; Wasylikowa et al., 2006; Djamali et al., 2010). Smooth increases in oak pollen contents from the early Holocene (~9 ka), with a sharp rise centred around 6.3 ka (see Fig. 4a in Stevens et al., 2006) may show a higher moisture availability in the mid-Holocene, with a subsequent peak in aridity at ~4.5 ka (Schmidt et al., in press).

## 4. Aridification and the impact on civilisations ancient and modern

The age results from South Golbaf lakebed, and potentially also from the Nimbluk basin (Section 3.3), indicate that substantial amounts of surface water existed in now arid parts of eastern Iran until at least 7.8 ka, but they do not provide a direct constraint on

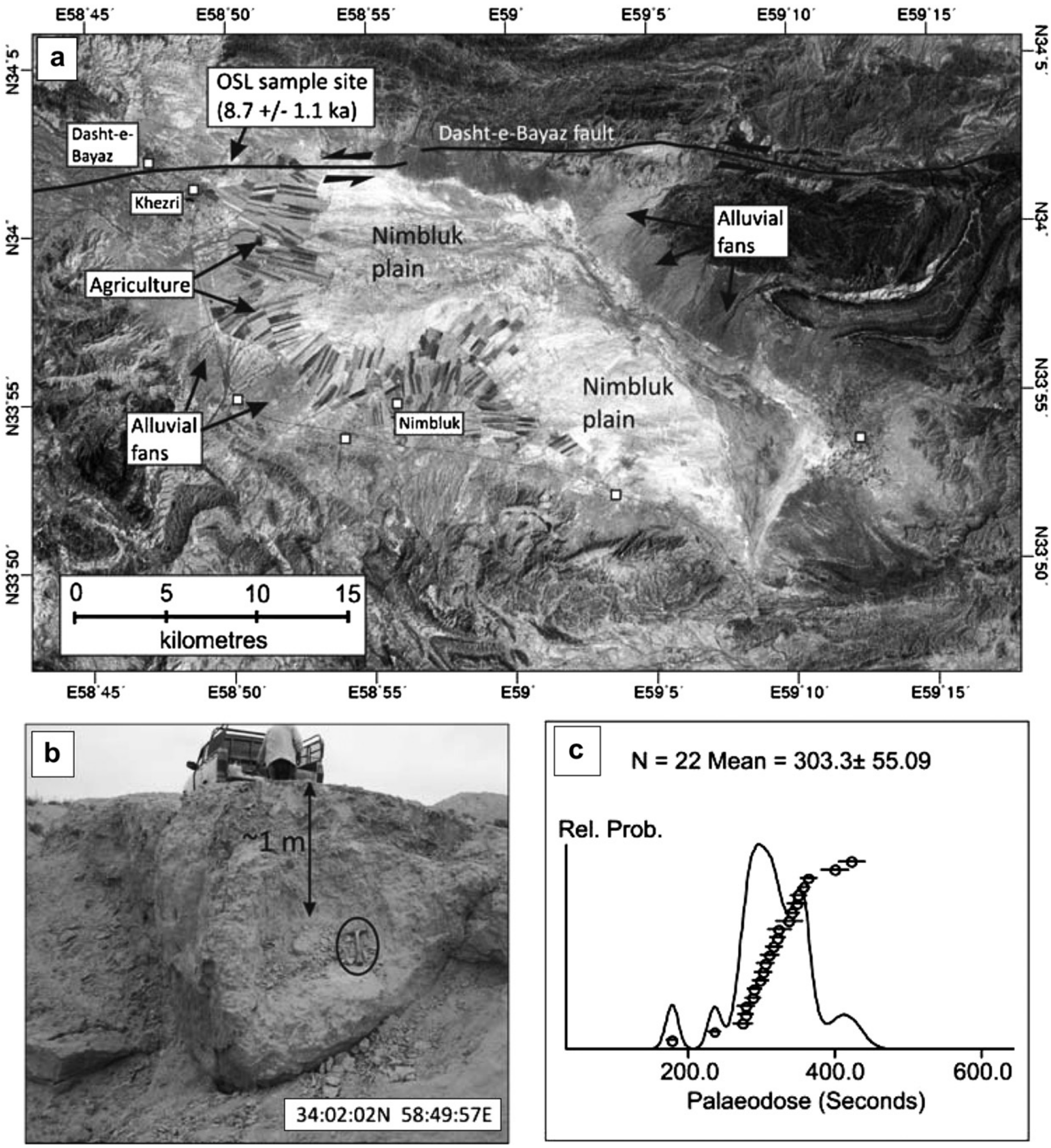


**Fig. 8.** LANDSAT ETM image of the Nimbluk plain at Dasht-e-Bayaz in northeast Iran. Settlements are marked by white squares. The settlements, and the farmed land, are concentrated in narrow strips at the edge of the basin. The basin floor, which shows up as a white shades in the satellite imagery, is composed of fine-grained fluvial deposits that are exposed at a few sites by movement along the east-west Dasht-e-Bayaz strike-slip fault. (b) Field photograph showing an exposure of fine-grained fluvial deposits of the Nimbluk basin. A single OSL sample of the sediment from ~1.25 m below the land surface (the sample location is marked by the geological hammer) was dated at 8.7 ± 1.1 ka (Fattahi et al., 2010b; Table 1). The widespread deposition of fluvial sediments, and subsequent incision of the plain by small streams, will thus date to sometime after 8.7 ± 1.1 ka. See part 'a' for location. (c) A probability density plot showing the distribution of equivalent doses for 22 aliquots of quartz grains isolated from the sample. The mean palaeodose of 303.3 ± 55.1 s is equivalent to 24.66 ± 2.74 Gy of beta dose. All sample preparation and analysis techniques are the same as those described in Fattahi et al. (2006).

when aridification began. The ages of lake highstand conditions from the two sites in eastern Iran are compatible with estimates of palaeo-rainfall from elsewhere in the eastern Mediterranean (e.g. Bar-Matthews et al., 2003), which show a moist climate in the early Holocene relative to today, a peak in moisture at 7.5 ka, followed by gradually increasing aridity, with sharp drops in rainfall at 5.2 a and 4.2 ka. The prolonged droughts at 4.2 and 5.2 ka are thought to have contributed to a decline in a number of complex agricultural

**Table 2**
Values used to calculate luminescence ages from fine-grained fluvial sediment in the fill of the Nimbluk basin, Dasht-e-Bayaz, NE Iran (Fig. 8; Fattahi et al. 2010a). U, Th and 40K contents were estimated from ICP-MS. The corrections applied for cosmic ray and moisture contents are all as described in Fattahi et al. (2006), and references therein.

| Sample | Grain (μm) | Water (%) | Depth (m) | K (%) | U (ppm) | Th (ppm) | Cosmic (Gy/ka) | Dose rate (mGy/yr) | De (Gy) | Age (ka) |
|---|---|---|---|---|---|---|---|---|---|---|
| DB | 90–150 | 5 | 1.25 | 1.420 ± 0.010 | 3.200 ± 0. 10 | 7.200 ± 0. 10 | 0.207 ± 0.135 | 2.82 ± 0.16 | 24.66 ± 2.74 | 8.7 ± 1.1 |

societies around the eastern Mediterranean and North African regions (e.g. Hassan and Stucki, 1987; Weiss, 2000; deMenocal, 2001; Staubwasser and Weiss, 2006). A drought at 4.2 ka, in particular, is correlated with abrupt collapse of the Akkadian empire in Mesopotamia (Weiss et al., 1993; Cullen et al. 2000; deMenocal, 2001).

Both the climate and archaeological records from eastern Iran are too sparse to be able to reach conclusions on the effect that any changes in environment had on the ancient inhabitants of the region. However, archaeological studies from southeast Iran (Adle, 2006; Fouache et al., 2008) do, potentially, provide support for a scenario of regional aridification in the mid- to late Holocene. Excavations around the city of Bam (Fig. 2) indicate a collapse of Bronze Age agricultural society towards the end of the 3rd Millennium BC. Re-establishment of agricultural societies ~1000 years later, was accompanied by a change from the construction of surface canals, to the development of the Qanat irrigation system of underground canal systems (Adle, 2006; Fouache et al., 2008), which are suited to the management of scarce water supplies (e.g Jackson, 2006). This correlation between the resurgence of agricultural society and the adoption of technology suited to scarce water supply may suggest that the region had become much drier. A decrease in the availability of surface water has also been cited as a potential reason for a shift to qanat irrigation technology in the early part of the Archaemenid period (from ~2.5 ka ago) at archaeological sites excavated near Sabzevar (Fouache et al., 2010; Fig. 2).

The adaptation to life in arid conditions in Iran has the potential to resonate to the present day in the exposure of populations to seismic hazard. Iran is one of the most earthquake-prone regions on the continents and many of the major population centres are close to active faults. Earthquakes in Iran thus cause frequent severe loss of life, such as at Rudbar-Tarom in 1990 (e.g. Berberian et al., 1992) and Bam in 2003 (e.g. Jackson et al., 2006), in each of which more than 30,000 people died. The striking correlation between the location of destructive earthquakes and centres of population is explained by the restricted availability of water, which is closely associated with the distribution of active faults: both by the channelling of ground waters along faults to form springs, and by the production over geological time of large mountain ranges that collect snow in winter and possess water tables that are elevated with respect to surrounding lowlands (e.g. Jackson, 2006).

## 5. Constraints on pre-Holocene alluvial fan deposition in eastern Iran

The pre-Holocene history of landscape development is not as well defined as for the Holocene. Regard et al. (2006) provide fan abandonment ages at 20.1 ± 1.5 ka and 44.0 ± 3.4 ka from Minab in SE Iran (Fig. 9). The first of these two events is not recognised at any of the other sites around eastern Iran, and in several studies the aggradation of alluvial sediment appears to have been continuous from at least 20 ka through to 10 ka (Fattahi et al., 2006; Hollingsworth et al., 2010; see Section 3).

The ~40 ka fan abandonment event at Minab is potentially also seen in two IRSL dates from the Uch Palang fan at Kashmar (Fattahi et al., 2007; Fig. 9), which indicate a period of deposition that ended in the range 40–60 ka. Ages consistent with an abandonment of range-front fan deposition at ~40 ka is also seen in fans displaced by the Neyshabour fault and dated between 35.4 ± 5.7 ka and 59.7 ± 10.3 ka by Hollingsworth et al. (2010), see Fig. 9, from two fan sequences dated at ~32 ka and ~55 ka from Astaneh in the Alborz mountains (Rizza et al., in press; Fig. 9), and from $^{36}$Cl

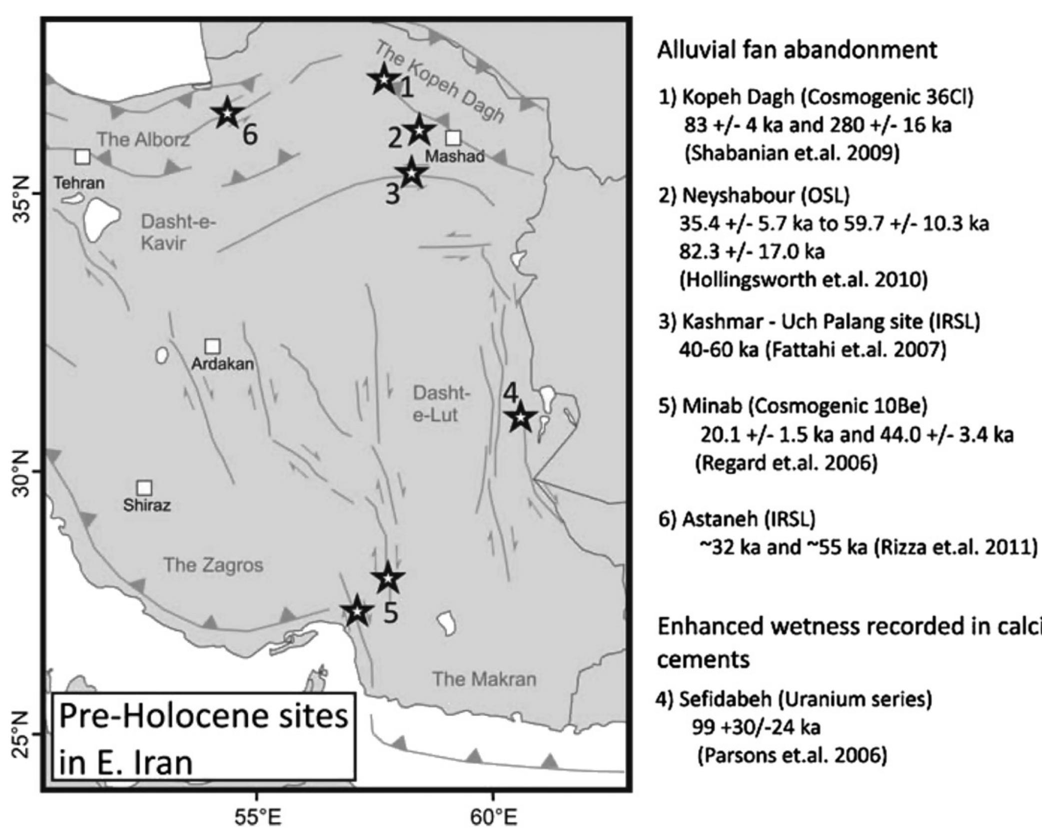


**Fig. 9.** Map showing the six sites (marked by white stars) where there are constraints on the pre-Holocene history of alluvial fan deposition in eastern Iran. Cold and arid conditions during the last glacial period are indicated by luminescence dating of aeolian deposits at Mashad and Ardakan.

exposure age of cobbles on a fan from the Zagros mountains in the range 36–69 ka (Authemayou et al., 2009; Fig. 1).

The Uch Palang fan, which is dated at 40–60 ka, appears to be displaced by ~150 m across the Doruneh left-lateral strike-slip fault (Fig. 10) providing an estimate of slip-rate on this fault of ~3 mm/yr that is similar to the Holocene rate of ~2.5 mm/yr estimated from the 25 m left-lateral displacement of the F1-T1 terrace riser at the Shesh Taraz incised river (Fattahi et al., 2007;

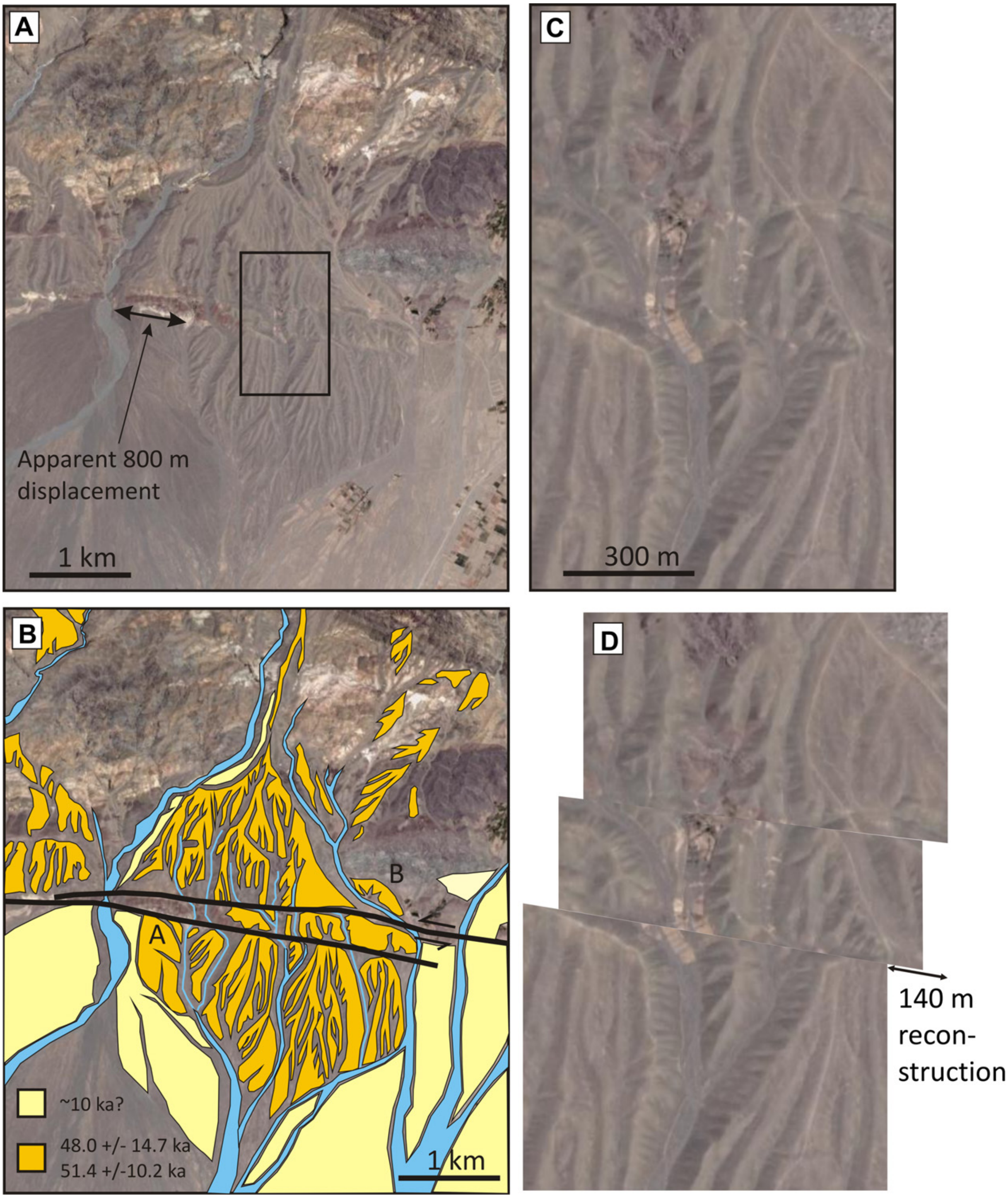


**Fig. 10.** (a) Quickbird satellite image (from GoogleEarth) showing an incised alluvial fan at Uch Palang near Kashmar. (b) Geomorphic interpretation of 'a'. Active streams are drawn in white (blue in the electronic version). Two generations of alluvial fan are identified. A widespread and slightly incised surface may correlate with the 10 ka surface that flanks the Shesh Taraz river ~50 km to the west of this site (Fattahi et al., 2007; Section 3.1.3). The more heavily incised surface in the centre of the image is dated at 40–60 ka (Fattahi et al., 2007). Remnants of the fan surface at 'A' on the south side of the fault, and at 'B' on the north side, are important in showing that the left-lateral displacement is much less than the 800 m originally estimated. (c) Close-up of the central part of the fan where the Doruneh fault left-laterally displaces drainage channels heavily incised into the fan surface. (d) Reconstruction of ~140 m of fault slip restores the incised drainage channels to straight courses. 140 m of slip in 40–60 ka yields a slip-rate of ~3 mm/yr that is similar to the ~2.5 mm/yr determined by Fattahi et al. (2007) from a ~25 m left-lateral displacement of 10 ka fan deposits flanking the Shesh Taraz river (see Section 3.1.3). Note that Fattahi et al. (2007) originally estimated a left-lateral displacement of ~800 m across the fan that is not supported by our observations of the high-resolution Quickbird imagery. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4). Other abandoned alluvial fans along the Kuh-e-Sorkh range-front, with similar degrees of dissection as seen at Uch Palang, appear to be displaced by ~150 m across the Doruneh fault (see, for example, the F2 fan surface in Fig. 4b) suggesting that the Uch Palang fan abandonment is regional at least at the scale of the Kuh-e-Sorkh mountain range. If the Uch Palang site is representative of the regional pattern of deposition across eastern Iran we would expect a change from fan deposition to incision of the landscape at 40–60 ka followed by a return to alluvial deposition by 30 ka or less (as observed at Sabzevar, Fattahi et al., 2006).

Hollingsworth et al. (2010) obtain OSL ages on two generations of alluvial fan deposits uplifted by movement on the Neyshabour thrust fault in the plains west of Neyshabour city (Fig. 9). The younger of these two fans, as described above, is dated from two OSL samples at between 35.4 ± 5.7 ka and 59.7 ± 10.3 ka. The older of the two fans is dated from a single OSL sample at 82.3 ± 7.0 ka. The OSL results show rather a large amount of scatter that might indicate that the sediment grains were not fully reset on deposition (see Hollingsworth et al., 2010 for a full description of results). A $^{36}$Cl cosmogenic dating study of limestone boulders exposed in alluvial fans in the Kopeh Dagh Mountains (with sites at latitudes 37°33′N and 37°41′N, Fig. 9) by Shabanian et al. (2009) yields an abandonment age of 83 ± 4 ka as well as a much older period of abandonment at 280 ± 16 ka.

Given the widespread change from fan deposition to dissection observed at ~10 ka (see Section 3) there are surprisingly few data supporting a similar regional change at the Penultimate Glacial-Last Interglacial transition at ~128 ka, when enhanced rainfall is recorded from spelaeothem records in Oman (Burns et al., 2003) and from Israel (Bar-Matthews et al., 2003). Parsons et al. (2006) obtain a U-series age of 99 + 30/−24 ka for calcite-cemented sandstones at Sefidabeh (30°58′N, Fig. 9), which were likely to have been deposited under conditions of at least seasonal wetness. Further support for moist environmental conditions at ~120 ka in Iran - though outside our core study region of eastern Iran - comes from an expansion of forests inferred from a core from lake Urmia in the NW of the country (Djamali et al., 2008) and from the thick development of soils in the Persepolis basin near Shiraz in the SW (Kehl et al., 2009; Fig. 9). Authemayou et al. (2009) infer a ~120 ka abandonment age for alluvial fans in the central Zagros from $^{36}$Cl exposure ages of surface cobbles in the range 121–169 ka (Fig. 1).

Overall, the studies that target features of pre-Holocene age are too few in number to fully constrain the palaeo-environmental conditions under which the features were formed, although there is limited evidence of early alluvial fan abandonments at 40–60 ka, at ~80 ka, and at ~120 ka. Further dating studies of penultimate and older cycles of alluvial fan deposition are required to determine the pre-Holocene history of landscape development in eastern and central Iran.

## 6. A scenario of Holocene environmental change in eastern Iran

Based on the available data we suggest that the most recent period of widespread mountain-front fan deposition in eastern Iran may have started from ~30 ka (e.g. Fattahi et al., 2006; Hollingsworth et al., 2010; Fig. 11a). The sedimentation may have been caused by a relatively high rate of sediment production through the action of freeze-thaw weathering in a cold and arid glacial environment (e.g. Poisson and Avouac, 2004). Cold and arid conditions in Iran during the last glacial maximum are supported by the accumulation between ~28.0–18.8 ka of 25 m of aeolian sand-ramp deposits, containing abundant frost-shattered scree, at Ardakan in central Iran (Fig. 1; Thomas et al., 1997) and by the development of up to 12 m of loess cover between 25.9 ± 1.8 ka and 13.7 ± 1.0 ka in the regions east of Mashad in NE Iran during the last glacial maximum and late glacial period (e.g. Karimi et al., 2011).

There is some indication that deposition of fan material continued until 5.8 ± 3.6 ka at Anar (Le Dortz et al., 2009). At Sabzevar, the alluvial fan surface must postdate 13 ± 0.7 ka, but must also predate the deposition of fine-grained deposits that overlie the surface, and which are dated at 9 ± 1 ka (Fattahi et al., 2006). These two sites are perhaps the best constrained of all those that we reviewed, with sampling of fine-grained deposits and, in the Sabzevar example, the in-situ measurement of dose rates with a portable gamma-spectrometer. Therefore, although the majority of the data from all sites are satisfied by a range of 10 ± 3 ka for the cessation of deposition along the mountain range-fronts, it appears as though the age of abandonment is towards the younger (early Holocene) part of this range (e.g. Fig. 11b). The deposition of fan material at mountain range-fronts therefore appears to have continued beyond the end of the cold and arid glacial period at ~13 ka (Karimi et al., 2011) by a period of several thousand years, implying either that large amounts of sediment were still being produced in the early Holocene or that a proportion of the sediment generated during the late glacial period was stored within mountainous regions and then transported during the early Holocene.

Fan abandonment was followed by river incision (Fig. 11c). Several cycles of river terrace formation and incision date within the early Holocene (Regard et al., 2006; Fattahi et al., 2007) and may have formed as a response to minor variations in environment during a time that was more humid than at present - as indicated by the deposition of lakebed sediments at South Golbaf and in the widespread deposition of fluvial sediments across the Nimbluk plain (Fattahi et al., 2010a; Walker et al., 2010; Fig. 11c). The apparent absence of landforms dating from the latter half of the Holocene suggest that the landscape has changed little over this time (Fig. 11d); presumably as a consequence of aridification in central and eastern Iran that may, in turn, have affected Bronze Age agricultural societies in the region (Fouache et al., 2008). We do not, however, have any direct constraint on the timing of this aridification.

The high mountain ranges of eastern Iran are generally bounded by active faults that play a role in shaping the landscape evolution by promoting incision within those parts of the landscape that are being uplifted. A landscape dominated by tectonic movements, rather than by environmental factors such as changes in precipitation and sediment availability, will show fluvial incision in regions of uplift that ends abruptly at the fault scarps. This type of morphology is observed in eastern Iran and is seen, for example, in the satellite images from Sabzevar (Fig. 3) and Bam (Fig. 7). However, the streams shown in the Sabzevar and Bam examples have very small catchments, little discharge, and possess consequently less erosive power (e.g. Schumm et al., 2002; Tucker and Whipple, 2002; Poisson and Avouac, 2004). Rivers that drain larger catchments and have greater discharge show patterns of incision that are not interrupted across the fault lines (see, for example, the Shesh Taraz river; Fig. 4). Although active faulting is clearly a factor in shaping the pattern of stream incision across eastern Iran, it is only the dominant factor in shaping the pattern of incision within small river catchments, and it is environmentally-driven variations in discharge that dominate in the larger catchments.

The scenario of Holocene landscape evolution that is primarily driven by changes in precipitation has been suggested in other parts of Asia. For instance, Poisson and Avouac (2004) show that a series of river terraces on the north flank of the Tien Shan in W. China were formed during periods of raised lake level in the adjacent Junggar basin. Also, Bookhagen et al. (2006), correlate

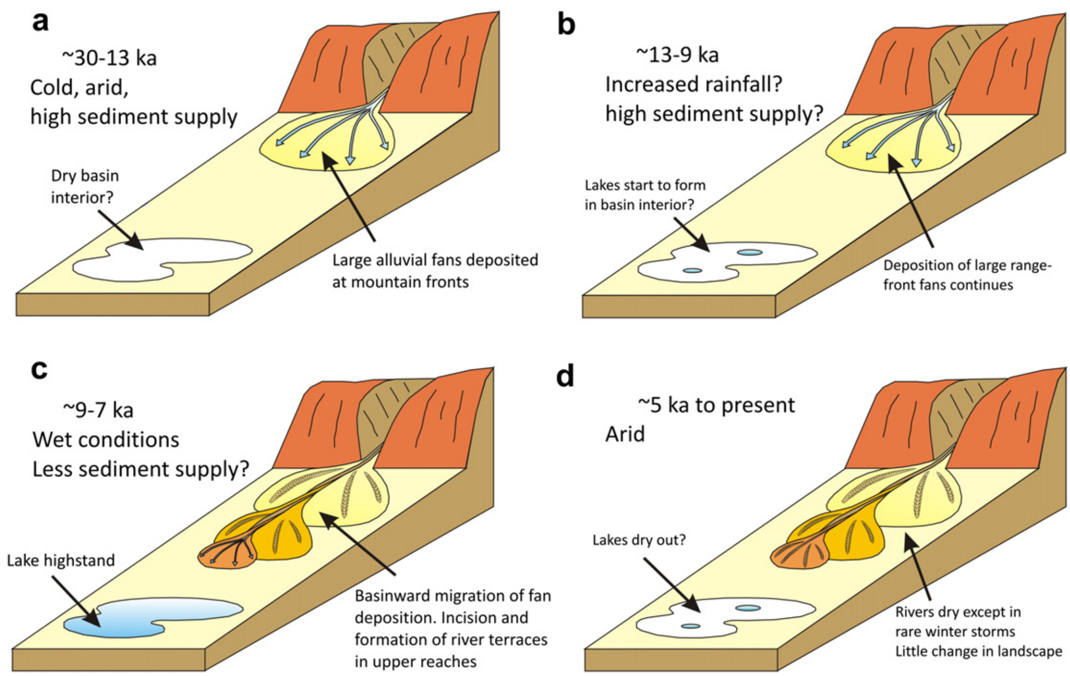


**Fig. 11.** A summary of the Last Glacial and Holocene palaeo-environmental changes suggested by the available age data in eastern Iran. (a) The deposition of large alluvial fans along the mountain range-fronts is likely to have started during the late glacial period with the production of large amounts of sediment in the cold and arid environment. (b) The range-front fan deposition appears to have continued into the earliest part of the Holocene. The widespread fan deposition may be accompanied by an increase in the amount of precipitation (inferred from the ending of loess deposition in NE Iran at $\sim$13.7 $\pm$ 1 ka; Karimi et al., 2011) combined with a plentiful supply of sediment. (c) The period from $\sim$9 ka through to at least $\sim$7 ka is marked by high lake levels indicating a relatively wet environment. Alluvial fan deposits at the mountain range-fronts are abandoned and incised due to a basinward migration of river-borne sediment deposition. The switch from sediment deposition to incision at the range-fronts may be a response to elevated rainfall coupled with a decreasing supply of sediment (e.g. Poisson and Avouac, 2004). (d) From the mid-Holocene it appears that river incision has slowed and the landscape has achieved roughly the form that is takes today. The slowing of landscape evolution may result from the onset of the arid climatic conditions that continue through to the present day.

a sequence of terraces of the Sutlej river in the Indian Himalaya to short-lived reductions in precipitation as a result of fluctuations in the strength of the Indian summer monsoon.

Determining the origin of the early Holocene increase in precipitation in eastern Iran is hindered by the absence of detailed local palaeoclimatic studies, and by the potential influence in Iran of both the Mediterranean (winter rainfall) and Monsoonal (summer rainfall) regimes during the Holocene (e.g. Fig. 1). Much of eastern Iran lies at present within the Mediterranean Winter Rainfall Belt (e.g. Meher-homji, 1971; Gasse, 2000; Regard et al., 2006; Ghasemi and Khalili, 2008; Fig. 1), and variations in rainfall within this regime might account for the apparently synchronous landscape development that we observe across the region. Palaeoclimate records from other presently arid parts of the eastern Mediterranean region do indeed show wet conditions and lake level maxima near the start of the Holocene (e.g. Neev and Hall, 1979; Goodfriend, 1990, 1991; Neev and Emery, 1995; Frumkin, 1997; Klinger et al., 2003). Increasing aridity from $\sim$7.5 ka to the present day is then observed in cave spelaeothem records, declining lake levels, and marine isotopic data (e.g. Fontugne and Calvert, 1992; Bar-Matthews et al., 1997, 2003; Arz et al., 2003; Klinger et al., 2003). However, cave spelaeothem records from northern Oman show enhanced monsoonal rainfall from $\sim$10.6 ka with a return of arid conditions by 6.3 ka (e.g. Fleitmann et al., 2007), and it is possible that southeastern parts of Iran were also subject to monsoonal rains during the early Holocene (e.g. Regard et al., 2006).

With the lack of direct palaeoclimatic data from the interior of Iran any climatic interpretation of the observed Holocene environmental change remains speculative. The difficulties in inferring the regional climatic history are compounded by the rather similar histories of environmental change, with a relatively wet early Holocene followed by increasing aridity, which might be expected to occur under the influence of either Monsoonal or Mediterranean winter rainfall climate regimes. It is possible that the landscapes in the north and south of our study area might have formed in response to completely different climatic conditions, and may hence exhibit differences in timing of environmental changes that are below the resolution of our existing age constraints.

## 7. Conclusions

We have described a scenario of late Quaternary changes in river hydrology and lake deposition in the presently arid desert regions of eastern and central Iran that were likely to have occurred during a period of increased moisture in the early to mid-Holocene. Although changes in base-level caused by tectonic movements will have caused local changes in the patterns of river incision and sediment deposition, the tectonic movements do not appear to have been the primary control in the development of the landscape we see at the present day. The inferred mid-Holocene aridification across eastern Iran is likely to have had a profound effect on the present day distribution of human populations, with towns and villages now concentrated along the mountain range-fronts, where there is a more abundant supply of water, but where the hazard from earthquakes is greatest. We anticipate that future studies of the late Quaternary history of desert regions in eastern Iran will add details on the framework presented in this review and will help understand the role that changes in the environment and climate have had on the geomorphological and archaeological record of eastern Iran.

## Acknowledgements

We thank all the funding bodies, organisations, and individuals within Iran who have supported our continued research. In particular, we thank Dr. M.M. Khatib and Dr. M. Zarrinkoub of the University of Birjand, and Dr. M. Talebian of the Geological Survey of Iran, for their help. We also thank the D. Thomas of the Oxford University Centre for the Environment, the Oxford Luminescence Dating Laboratory, and the NERC-funded COMET centre in the UK. We are grateful to Matthew Jones for comments on an early draft of the manuscript and to two anonymous reviewers for their helpful suggestions. This work was made possible by grants from the Leverhulme Trust and the Royal Society of London. RTW is supported by a University Research Fellowship from the Royal Society.

## References

Adle, C., 2006. Qanats of Bam: and archaeological perspective. Irrigation system in Bam, its birth and evolution from the prehistoric period up to modern Times. In: Honari, M., et al. (Eds.), Qanats of Bam. A Multidisciplinary Approach. UNESCO Tehran Cluster Office, p. 158.

Ambraseys, N.N., Melville, C.P., 1982. A History of Persian Earthquakes. Cambridge University Press, UK.

Ambraseys, N.N., Tchalenko, J.S., 1969. The Dasht-e-Bayaz (Iran) earthquake of August 31, 1968: a field report. Bulletin of the Seismological Society of America 59, 1751–1792.

Arz, H.W., Lamy, F., Patzold, J., Muller, P.J., Prins, M., 2003. Mediterranean moisture source for an aarly-Holocene humid period in the northern Red Sea. Science 300, 118–121.

Authemayou, C., Bellier, O., Chardon, D., Benedetti, L., Malekzade, Z., Claude, C., Angeletti, B., Shabanian, E., Abbassi, M.R., 2009. Quaternary slip-rates of the Kazerun and the Main Recent Faults: active strike-slip partitioning in the Zagros fold-and-thrust belt. Geophysical Journal International 178, 524–540.

Bar-Matthews, M., Ayalon, A., Kaufman, A., 1997. Late Quaternary Palaeoclimate in the Eastern Mediterranean region from stable isotope analysis of speleothems at Soreq cave, Israel. Quaternary Research 47, 155–168.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., Hawkesworth, C.J., 2003. Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for palaeorainfall during interglacial intervals. Geochimica et Cosmologica Acta 67, 3181–3199.

Berberian, M., Yeats, R.S., 1999. Patterns of historical earthquake rupture in the Iranian Plateau. Bulletin of the Seismological Society of America 89, 120–139.

Berberian, M., Qorashi, M., Jackson, J.A., Priestley, K., Wallace, T., 1992. The Rudbar-Tarom earthquake of June 20, 1990 in NW Persia: Preliminary field and seismological observations, and its tectonic significance. Bulletin of the Seismological Society of America 82, 1726–1755.

Bookhagen, B., Fleitmann, D., Nishiizumi, K., Strecker, M.R., Thiede, R.C., 2006. Holocene monsoonal dynamics and fluvial terrace formation in the northwest Himalaya, India. Geology 34, 601–604.

Bottema, S., 1986. A late Quaternary pollen diagram from lake Urmai (Northwestern Iran). Review of Palaeobotany and Palynology 47, 241–261.

Brookes, 1982. Geomorphologic evidence for climatic change in Iran during the last 20,000 years. In: Blintiff, J.L., van Zeist, W. (Eds.), Palaeoclimates, Paleoenvironments and Human Communities in the Eastern Mediterranean Region in Later Prehistory. BAR International Series, 133.

Brown, E.T., Molnar, P., Bourlès, D.L., 2005. Technical comment on "Slip-rate measurements on the Karakorum Fault may imply secular variations in fault motion. Science 309, 1326b.

Burns, S.J., Fleitmann, D., Matter, A., Kramers, J., Al-Subbary, A.A., 2003. Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13. Science 301, 1365–1367.

COHMAP members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

Cullen, H.M., deMenocal, P.B., deMenocal, P.B., Hemming, G., Brown, F.H., Guilderson, T., Sirocko, F., 2000. Climate change and the collapse of the Akkadian empire: evidence from the deep Sea. Geology 28, 379–382.

deMenocal, P.B., 2001. Cultural responses to climate change during the late Holocene. Science 292, 667–673.

Djamali, M., et al., 2008. A late Pleistocene long pollen record from Lake Urmia, NW Iran. Quaternary Research 69, 413–420.

Djamali, M., et al., 2010. Indian Summer Monsoon variations could have affected the early-Holocene woodland expansion in the Near East. The Holocene 20, 813–820.

Duller, G.A.T., 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. Boreas 37, 589–612. doi:10.1111/j.1502-3885.2008.00051.x.

Fattahi, M., Walker, R., 2007. Luminescence dating of the last earthquake of the Sabzevar thrust fault, NE Iran. Quaternary Geochronology 2, 284–289.

Fattahi, M., Walker, R., Hollingsworth, J., Bahroudi, A., Nazari, H., Talebian, M., Armitage, S., Stokes, S., 2006. Holocene slip-rate on the Sabzevar thrust fault, NE Iran, determined using optically stimulated luminescence (OSL). Earth and Planetary Science Letters 245, 673–684. http://bullard.esc.cam.ac.uk/%257Erwalker/pdf/2006_sabzevar_epsl.pdf.

Fattahi, M., Walker, R.T., Khatib, M.M., Dolati, A., Bahroudi, A., 2007. Slip-rate estimate and past earthquakes on the Doruneh fault, eastern Iran. Geophysical Journal International 168, 691–709.

Fattahi, M., Nazari, H., Bateman, M.D., Meyer, B., Sebrier, M., Talebian, M., Le Dortz, K., Foroutan, M., Ahmadi Givi, F., Ghorashi, M., 2009. Refining the age of the last earthquake on the Dheshir fault, Central Iran. Quaternary Geochronology. doi:10.1016/j.quageo.2009.04.005.

Fattahi, M., Talebian, M., Tabatabaei, 2010a. Applying OSL to Determine the Bam-Baravat Fault Uplift Rate. UK TL/OSL/ESR Meeting 2010, 8-10th September. University of Oxford.

Fattahi, M., Walker, R., Khatib, M.M., Zarrinkoub, M., 2010b. Optical Dating of Holocene Lake-bed Sediments from the Nimbluk Plain, Khorasan, NE Iran: Implications for the Palaeo-environment of Iran. Oral Presentation, Geological Survey of Iran Annual Conference, 2010.

Fleitmann, D., Burns, S.J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary, A.A., Buettner, A., Hippler, D., Matter, A., 2007. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quaternary Science Reviews 26, 170–188.

Fontugne, M., Calvert, S.E., 1992. Late Pleistocene variability of the carbon isotopic composition of organic matter in the Eastern Mediterranean: monitor of changes in carbon sources and atmosphere CO2 concentrations. Palaeooceanography 7, 1–20.

Fouache, E., Cosandey, C., Adle, C., Casanova, M., Francfort, H.P., Madjidzadeh, Y., Tengberg, M., Sajadi, M., Shirazi, Z., Vahdati, A., 2008. A study of the climatic crisis of the end of the third Millenium BC in Southeastern Iran through the lens of geomorphology and archaeology. Proceedings of the 10th Annual Symposium on Iranian Archaeology, Bandar Abbas, Iran.

Fouache, E., Francfort, H.-P., Bendezu-Sarmiento, J., Vahdati, A.A., Lhuillier, J., 2010. The horst of Sabzevar and regional water resources from the Bronze Age to the present day (Northeastern Iran). Geodinamica Acta 23, 287–294.

Frumkin, A., 1997. The Holocene History of Dead Sea Levels. In: Niemi, T.M., Ben-Avraham, Z., Gat, J.R. (Eds.), The Lake and Its Setting. Oxford Monographs on Geology and Geophysics, 36. Oxford University Press, pp. 237–248. The Dead Sea.

Gasse, F., 2000. Hydrological changes in the African tropics since the last glacial maximum. Quaternary Science Reviews 19, 189–211.

Ghasemi, A.R., Khalili, D., 2008. The association between regional and global atmospheric patterns and winter precipitation in Iran. Atmospheric Research 88, 116–133.

Giessner, K., Hagedorn, H., Sarvati, M., 1984. Geomorphological studies in the Kashmar region, (NE Iran). Neues Jahrbuch fur Geologie und Palaontologie 168, 545–557.

Goodfriend, G.A., 1990. Rainfall in the Negev Desert during the middle Holocene, based on $^{13}C$ of organic matter in land snail shells. Quaternary Research 34, 187–196.

Goodfriend, G.A., 1991. Holocene trends in $^{18}O$ in land snail shells from the Negev Desert and their implications for changes in rainfall source areas. Quaternary Research 35, 417–426.

Hassan, F.A., Stucki, B.R., 1987. Nile floods and climatic change. In: Rampino, M.R., et al. (Eds.), Climate: History, Periodicity and Predictability. Van Nostrand Reinhold, pp. 37–46.

Hollingsworth, J., Fattahi, M., Walker, R., Talebian, M., Bahroudi, A., Bolourchi, M.J., Jackson, J., Copley, A., 2010. Oroclinal bending, distributed thrust and strike-slip faulting, and the accommodation of Arabia-Eurasia convergence in NE Iran since the Oligocene. Geophysical Journal International. doi:10.1111/j.1365-246X.2010.04591.x.

Jackson, J., Bouchon, M., Fielding, E., Funning, G., Ghorashi, M., Hatzfeld, D., Nazari, H., Parsons, B., Priestley, K., Talebian, M., Tatar, M., Walker, R., Wright, T., 2006. Seismotectonic, rupture-process, and earthquake-hazard aspects of the 26 December 2003 Bam, Iran, earthquake. Geophysical Journal International 163, 90–105.

Jackson, J., 2006. Fatal attraction: living with earthquakes, the growth of villages into megacities, and earthquake vulnerability in the modern world. Philosophical Transactions of the Royal Society A 364, 1911–1925.

Jones, M., Djamali, M., Stevens, L., Heyvaert, V., Askari, H., Norolahie, D., Weeks, L., 2011. Mid Holocene environmental and climatic change in Iran. In: ancient Iran and its neighbours. In: Petrie, C. (Ed.), Local Developments and Long-range Interactions in the 4th Millenium BC.

Karimi, A., Frechen, M., Khademi, H., Kehl, M., Jalalian, A., 2011. Chronostratigraphy of loess deposits in northeast Iran. Quaternary International 234, 124–132.

Kehl, M., Frechen, M., Skowronek, A., 2009. Nature and age of late Quaternary basin fill deposits in the basin of Persepolis/Southern Iran. Quaternary International 196, 57–70.

Klinger, Y., Avouac, J.-P., Bourles, D., Tisnerat, N., 2003. Alluvial deposition and lake-level fluctuations forced by Late Quaternary climate change: the Dead Sea case example. Sedimentary Geology 162, 119–139.

Le Dortz, K., Meyer, B., Sebrier, M., Nazari, H., Braucher, R., Fattahi, M., Benedetti, L., Foroutan, M., Siame, L., Bourles, D., Talebian, M., Bateman, M.D., Ghoraishi, M., 2009. Holocene right-slip rate detemrined by cosmogenic and OSL dating on the Anar fault, Central Iran. Geophysical Journal International 179, 700–710. doi:10.1111/j.1365-246X.2009.04309.x.

Meher-homji, V.M., 1971. On the Mediterranean climatic regime of west Pakistan. Theoretical and Applied Climatology 19, 277–286.

Meyer, B., Le Dortz, K., 2007. Strike-slip kinematics in Central and Eastern Iran: estimating fault slip-rates averaged over the Holocene. Tectonics 26 TC5009, doi:10.1029/2006TC002073.

Mildrexler, D.J., Zhao, M., Running, S.W., 2006. Where are the hottest spots on Earth. Eos 87 (43), 461–476.

Neev, D., Hall, J.K., 1979. Geophysical investigations in the Dead Sea. Sedimentary Geology 23, 209–238.

Neev, D., Emery, K.O., 1995. The Destruction of Sodom, Gomorrah, and Jericho. Oxford University Press.

Owen, L.A., Finkel, R.C., Haizhou, M., Barnard, P.L., 2006. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: a framework for examining the links between glaciation, lake level changes and alluvial fan formation. Quaternary International 154, 73–86.

Parsons, B., Wright, T., Rowe, P., Andrews, J., Jackson, J., Walker, R., Khatib, M., Talebian, M., Bergman, E., Engdahl, E.R., 2006. The 1994 Sefidabeh (eastern Iran) earthquakes revisited: new evidence from satellite radar interferometry and carbonate dating about the growth of an active fold above a blind thrust fault. Geophysical Journal International 164, 202–217.

Poisson, B., Avouac, J.-P., 2004. Holocene hydrological changes inferred from alluvial stream entrenchment in North Tien Shan Northwest China. The Journal of Geology 189, 231–249.

Potts, D.T., 2003. Tepe Yahya, Tell Abraq and the chronology of the Bampur sequence. Iranica Antiqua 38, 1–24.

Pratt, B., Burbank, D.W., Heimsath, A., Ojha, T., 2002. Impulsive alluviation during early Holocene strengthened monsoons, central Nepal Himalaya. Geology 30, 911–914.

Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research 59, 255–261. doi:10.1016/S0033-5894(03)00006-1.

Regard, V., Bellier, O., Thomas, J.-C., Bourles, D., Bonnet, S., Abbassi, M.R., Braucher, R., Mercier, J., Shabanian, E., Soleymani, Sh, Feghhi, Kh, 2005. Cumulative right-lateral fault slip-rate across the Zagros-Makran transfer zone: role of the Minab-Zendan fault system in accommodating Arabia-Eurasia convergence in southeast Iran. Geophysical Journal International 162, 177–203.

Regard, V., Bellier, O., Braucher, R., Gasse, F., Bourles, D., Mercier, J., Thomas, J.-C., Abbassi, M.R., Shabanian, E., Soleymani, Sh, 2006. 10Be dating of alluvial deposits from southeastern Iran (the Hormoz Strait area). Palaeogeography, Plaeoclimatology, Palaeoecology 242, 36–53.

Rigot, J.-B., 2010. Dynamique de la riviere Poulvar et morphogenese de la plaine de Tang-i-Bulaghi (Fars, Iran) a l'Holocene: Premiers resultats. Geomorphologie 1, 57–72.

Rizza, M., Mahan, S., Ritz, J-F., Nazari, H., Hollingsworth, J., Salamati, R. Using luminescence dating of coarse matrix material to estimate the slip rate of the Astaneh fault, Iran. Quaternary Geochronology, in press.

Schumm, S.A., Dumont, J.F., Holbrook, J.M., 2002. Active Tectonics and Alluvial Rivers. Cabridge University Press, UK.

Shabanian, E., Siame, L., Bellier, O., Benedetti, L., Abbassi, M., 2009. Quaternary slip rates along the northeast boundary of the Arabia-Eurasia collision zone (Kopeh Dagh Mountains, north-east Iran). Geophysical Journal International 178, 1055–1077.

Schmidt, A., Quigley, M., Fattahi, M., Azizi, G., Maghsoudi, M., Fazeli, H. Holocene settlement shifts and palaeoenvironments on the Central Iranian Plateau: disentangling linked systems. The Holocene, in press.

Snyder, J.A., Wasylik, K., Fritz, S.C., Wright, H.E., 2001. Diatom-based conductivity reconstruction and palaeoclimatic interpretation of a 40-ka record from Lake Zeribar, Iran. The Holocene 11, 737–745.

Staubwasser, M., Weiss, H., 2006. Holocene climate and cultural evolution in late prehistoric-early historic West Asia. Quaternary Research 66, 372–387.

Street, F.A., Grove, A.T., 1979. Global maps of lake-level fluctuations since 30,000 Years bp. Quaternary Research 12, 83–118.

Stevens, L.R., Ito, E., Schwalb, A., Wright, H.E., 2006. Timing of atmospheric precipitation in the Zagros Mountains inferred from a multi-proxy record from Lake Mirabad, Iran. Quaternary Research 66, 494–500.

Talebian, M., Tabatabaei, S.H., Fattahi, M., Ghorashi, M., Beitollahi, A., Ghalandarzadeh, A., Riahi, M.A., 2010. Estimating slip rates of faults around Bam and their application in Evaluation of earthquake hazard. Geosciences 19 (74), 149–156 (in Farsi, with English abstract).

Thomas, D.S.G., Bateman, M.D., Mehrshahi, D., O'Hara, S.L., 1997. Development and environmental significance of an eolian sand ramp of last-glacial age, Central Iran. Quaternary Research 48, 155–161.

Tucker, G.E., Whipple, K.X., 2002. Topographic outcomes predicted by stream erosion models: sensitivity analysis and intermodel comparison. Journal of Geophysical Research 107, 2179–2194.

Walker, R., Jackson, J., 2002. Offset and evolution of the Gowk fault, S.E. Iran: a major intra-continental strike-slip system. Journal of Structural Geology 24, 1677–1698.

Walker, R., Jackson, J., Baker, C., 2003. Surface expression of thrust faulting in eastern Iran: source parameters and surface deformation of the 1978 Tabas and 1968 Ferdows earthquake sequences. Geophysical Journal International 152, 749–765.

Walker, R.T., Talebian, M., Sloan, R.A., Rasheedi, A., Fattahi, M., Bryant, C., 2010. Holocene slip-rate on the Gowk strike-slip fault and implications for the distribution of tectonic strain in eastern Iran. Geophysical Journal International. doi:10.1111/j.1365-246X.2010.04538.x.

Wasylikowa, K., Witkowski, A., Walanus, A., Hutorowicz, A., Alexandrowicz, S.W., Langer, J.J., 2006. Palaeolimnology of Lake Zeribar, Iran, and its climatic implications. Quaternary Research 66, 477–493.

Weiss, H., Courty, M.A., Wetterstorm, W., Guichard, F., Senior, L., Meadow, R., Curnow, A., 1993. The genesis and collapse of third millenium north Mesopotamia civilisation. Science 261, 995–1004.

Weiss, H., 2000. Beyond the younger Dryas collapse as adaptation to abrupt climate change in ancient west Asia and the eastern Mediterranean. In: Bawden, G., Reycraft, R. (Eds.), Confronting Disaster: Engaging the Past to Understand the Future. University of New Mexico Press, pp. 75–98.