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Holocene settlement shifts and palaeoenvironments on the Central Iranian Plateau: investigating linked systems

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Abstract

For thousands of years, humans have inhabited locations that are highly vulnerable to the impacts of climate change, earthquakes, and floods. In order to investigate the extent to which Holocene environmental changes may have impacted on cultural evolution, we present new geologic, geomorphic, and chronologic data from the Qazvin Plain in northwest Iran that provides a backdrop of natural environmental changes for the simultaneous cultural dynamics observed on the Central Iranian Plateau. Well-resolved archaeological data from the neighbouring settlements of Zagheh (7170-6300 yr BP), Ghabristan (6215-4950 yr BP) and Sagzabad (4050-2350 yr BP) indicate that Holocene occupation of the Hajiarab alluvial fan was interrupted by a 900 year settlement hiatus. Multi-proxy climate data from nearby lakes in northwest Iran suggest a transition from arid early Holocene conditions to more humid middle Holocene conditions from ca. 7550-6750 yr BP, coinciding with the settlement of Zagheh, and a peak in aridity at ca. 4550 yr BP during the settlement hiatus. Palaeoseismic investigations indicate that large active fault systems in close proximity to the tell sites incurred a series of large (M_W ~7.1) earthquakes with return periods of ~500-1000 years during human occupation of the tells. Mapping and optically stimulated luminescence (OSL) chronology of the alluvial sequences reveals changes in depositional style from coarse grained unconfined sheet flow deposits to proximal channel flow and distally prograding alluvial deposits sometime after ca. 8830 yr BP, possibly reflecting an increase in moisture following the early Holocene arid phase. The coincidence of major climate changes, earthquake activity, and varying sedimentation styles with changing patterns of human occupation on the Hajiarab fan indicate links between environmental and anthropogenic systems. However, temporal coincidence does not necessitate a fundamental causative dependency.

Keywords

Settlement, palaeoenvironment, climate, tectonics, geomorphology, alluvial fan, OSL, Iran

1. Introduction

The Holocene era (ca. 11,500 yr BP to present[1]) encompasses the growth and development of modern societies, the evolution of important ecosystems, and rapid climate change (Mayewski *et al.* 2004; Anderson *et al.* 2007). Holocene climate change and environmental catastrophes such as earthquakes, floods, and volcanoes are often invoked to explain changes of culture and social complexity, and in human settlement patterns (Berberian & Yeats 2001; Haug *et al.* 2003; Brooks 2006; Staubwasser & Weiss 2006; Kaniewski *et al.* 2008). For example, the collapse of the Akkadian empire in Mesopotamia at ca. 4200 yr BP has been attributed to increased aridity (Cullen *et al.* 2000; deMenocal 2001) and increased mid-Holocene aridity is interpreted to have led to substantial dislocations of populations and abandonment of some regions across Mesopotamia (Hole 1994), Egypt (Wendorf & Schild 1998; Linstädter & Kröpelin 2004), and the modern India-Pakistan border area (Staubwasser *et al.* 2003; Staubwasser & Weiss 2006). However, many human settlements across the globe have grown from primitive mid-Holocene villages into cities and megacities despite being situated in locations highly susceptible to natural disasters, suggesting that catastrophic environmental forcing and/or risk is not sufficient to deter settlement of geographically or strategically desirable locations (Bilham 1998; Jackson 2006). For example, the predecessor habitations of the city of Tehran, Iran were damaged or destroyed completely by $M_W \sim 7$ earthquakes ca. 6000 years ago and at AD 855, 958, 1177 and 1830 (Ambraseys & Melville 1982; Berberian & Yeats 1999) yet the city has grown to its present metropolitan population of more than 13 million. How sensitive were ancient civilizations to environmental forcing? Did changes in climate or the occurrence of natural disasters influence social, cultural, economic, and technological development? Linked archaeological, palaeoenvironmental, and geologic investigations provide a means to study these important questions that may yield insight into the core of human society (e.g. Boyer *et al.* 2006).

In this paper we present new geologic, geomorphic and chronologic datasets that are used to provide a palaeoenvironmental context for the cultural evolution of the settlements of Zagheh (7170-6300 yr BP), Ghabristan (6215-4950 yr BP) and Sagzabad (4050-2350 yr BP) on the Central Iranian Plateau (Figs 1 & 2). Many settlements in Iran, including these sites, are situated on active alluvial fans, which pose flood and sediment inundation hazards, but provide fertile soils for agriculture. Furthermore, many settlements are situated close to active faults, which are sources of large earthquakes but provide conduits for water, thus justifying the so-called ‘fatal attraction’ of humans to earthquake-prone locations (Jackson 2006). In order to investigate whether climatic and/or tectonic processes were sufficient to influence human settlement patterns, we conducted geologic and geomorphic mapping of nearby active faults and late Quaternary sedimentary deposits on and adjacent to the Hajiarab alluvial fan (Fig. 2), upon which these settlements developed beginning approximately 8000 years ago. By combining such mapping with stratigraphic analysis, optically stimulated luminescence chronology (OSL) and archaeological information (Negahban 1977; Fazeli *et al.* 2005; Schmidt & Fazeli 2007), we show that while climatic and tectonic processes provide feasible environmental drivers to contextualise settlement and abandonment patterns on the Hajiarab fan, drawing deterministic conclusions is not possible.

[1] All dates in this publication are calibrated years BP. Archaeological ages are quoted by using AD 1950 as 0 yr BP.

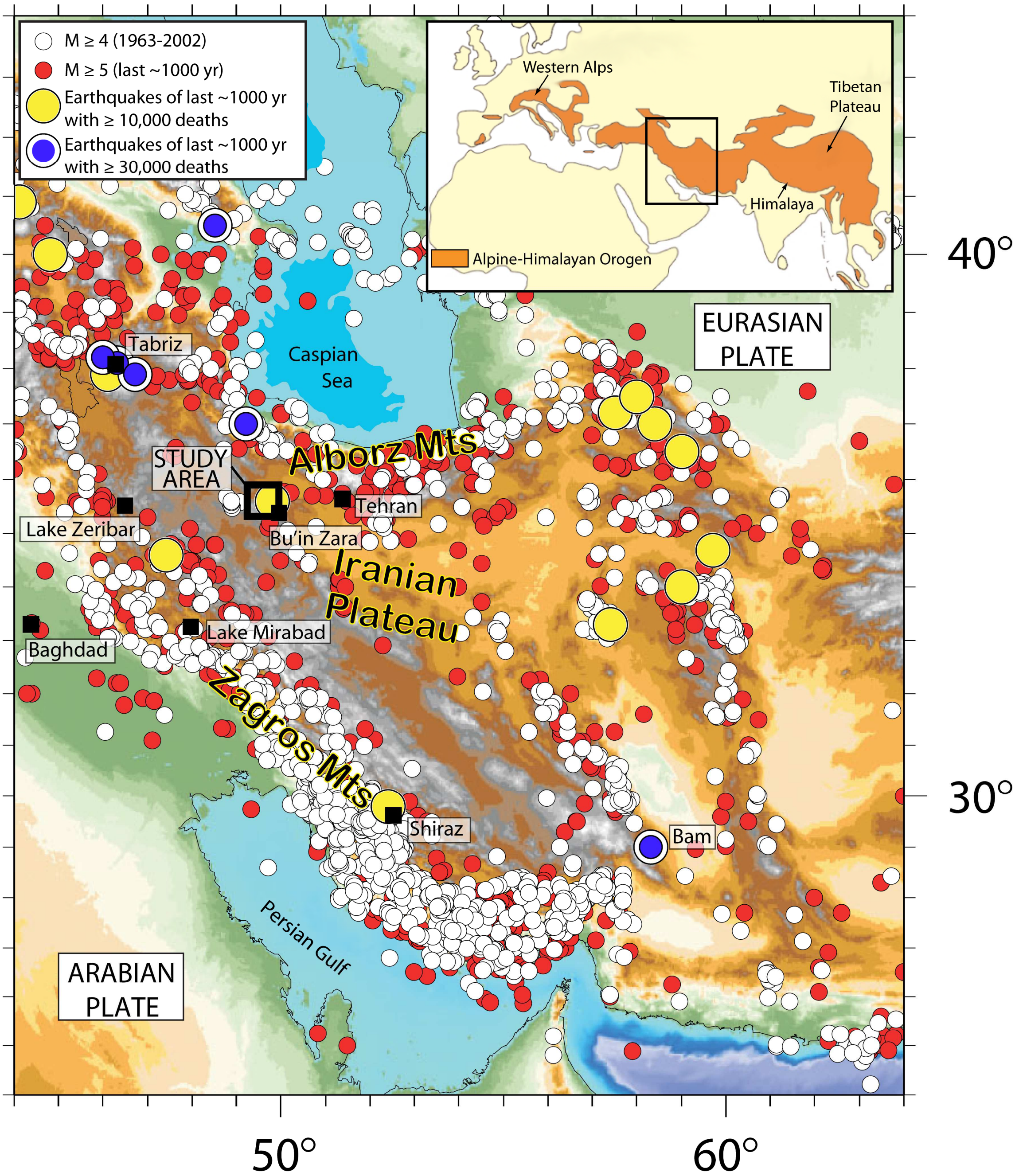

Figure 1. (Inset) The Alpine-Himalayan Orogen, which results from the tectonic collision of the Eurasian plate with the African, Arabian and Indian plates to the south. (Main) Earthquakes in Iran and its surroundings. White dots are well-located earthquakes of M_w > 4 during 1963–2002, from Engdahl et al. (2006). Red dots are earthquakes of the previous 1000 years, thought to be of M_w>5, from Ambraseys and Melville (1982). Larger dots are earthquakes of the last 1000 years that have killed more than 10,000 people (yellow dots) and 30,000 people (blue dots). Note the close spatial relationship of several of these large earthquakes to major urban centres. Location of study area (described in Fig 2) as shown. Modified from Jackson (2006).

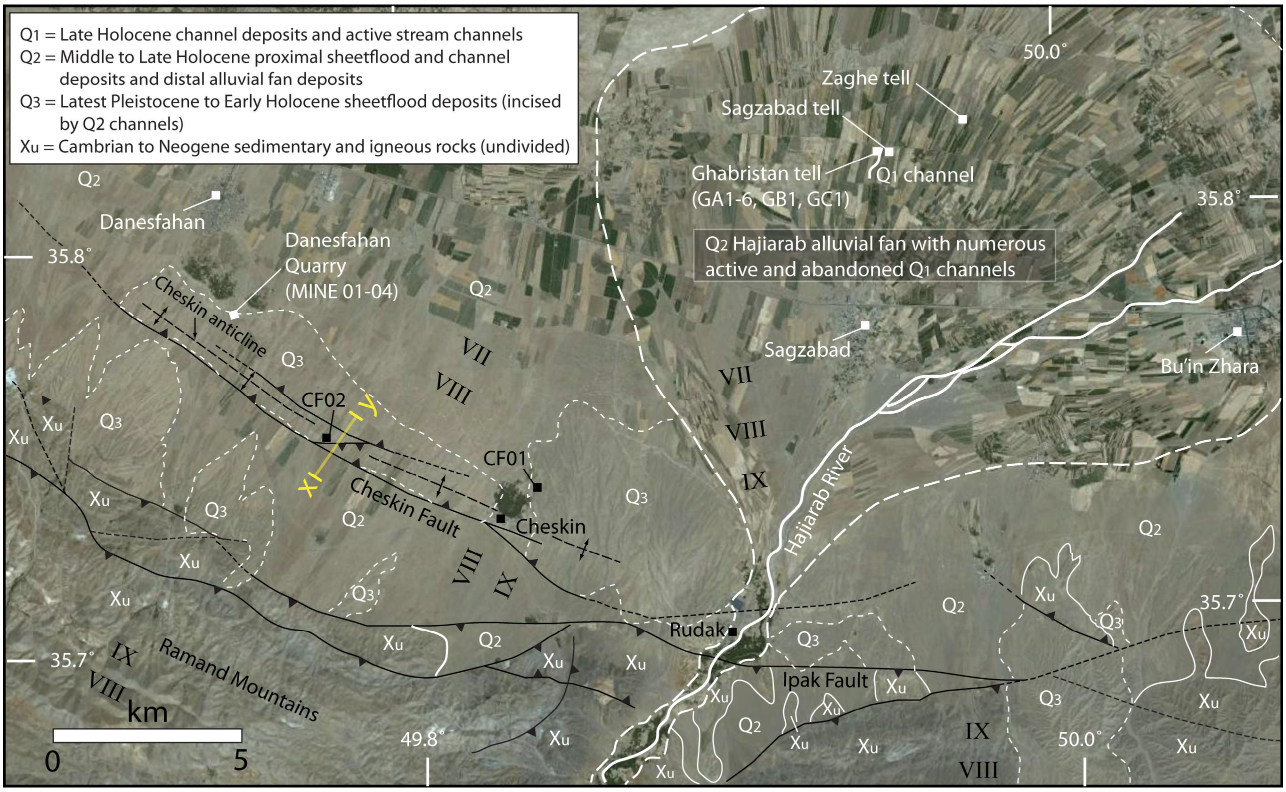

Figure 2. Geologic and geomorphic sketch map of the study area, showing locations of active faults and folds (Ipak Fault, Cheskin Fault, Cheskin Anticline), bedrock outcrops, Late Pleistocene and Holocene alluvial sequences (Q_1-Q_3) and settlements, including the settlements of the Sagzabad Cluster. Locations of OSL samples and corresponding sample codes, and location of topographic cross-section X-Y (Fig. 5) as shown. Fault positions as dashed where inferred. Position of Ipak Fault slightly modified from Berberian and Yeats (2001) and Ambraseys (1963) to adhere to topographic/geologic features.

2. Archaeological context

This project focuses on three prominent tells (the 'Sagzabad Cluster') that are situated on the Hajiarab alluvial fan, part of the Qazvin alluvial plain on the Central Iranian Plateau of northwest Iran, in the south part of the central Alborz Mountains. The Ramand Mountains lie approximately 15 km to the south (Fig. 2). The tells are located within a distance of 2.6 km of each other and form a settlement sequence, being established on successively aggraded fan surfaces (Fig. 3). The oldest, Zagheh, was occupied during the Transitional Chalcolithic period, and radiocarbon samples from sealed contexts (Fazeli *et al.* 2005) dated the earliest settlement layer to 7170 yr BP (±156 yrs[2]) and the latest to 6300 yr BP (±110 yrs), at 4.6 m and 0.4 m below the current ground surface, respectively. However a lowest depth of 6.1 m is mentioned in reports from earlier excavations (Negahban 1977). Due to the aggradation of alluvial layers the site is now nearly entirely buried (Schmidt & Fazeli 2007). The oldest radiocarbon sample for the second site, Ghabristan, dates to 6215 yr BP (±105 yrs) at a depth of 5.3 m, 0.3 m above 'virgin soil' (i.e. sediments without cultural material). From this Early Chalcolithic period the site was continuously occupied until around 4950 yr BP, the end of the Late Chalcolithic period (Fazeli *et al.* 2005). After its abandonment, a gap of about 900 years is evident in the archaeological record. No occupation has been detected in the Qazvin Plain for this period of the Early Bronze Age apart from Shizar Tepe, at the southeastern edge of the plain. This lack of evidence for occupation over nearly a millennium is consistent with a simultaneous settlement hiatus documented in the eastern part of the Central Iranian Plateau

[2] All radiocarbon dates are calibrated using OxCal V4.0 (Bronk Ramsey 1995, 2001) and errors are given for the 96% confidence range, equivalent to 2 standard deviations.

(Coningham *et al.* 2004; Coningham *et al.* 2006). Subsequently, habitation started again in the Middle Bronze Age at around 4050 yr BP at the site of Sagzabad (Fazeli Nashli & Abbasnezhad Sereshti 2005), just 0.3 km east of Ghabristan, and carried on well into the Iron Age, to around 2350 yr BP (Malek Shahmirzadi 1977). Its lowest currently visible levels are 2.7 m below the ground surface and the top of the site still stands 7 m high above the surrounding alluvial plain. In the topmost levels of Ghabristan many Iron Age graves were discovered (now destroyed through looting) demonstrating its use as burial ground for the inhabitants of Sagzabad, probably around 2500 yr BP.

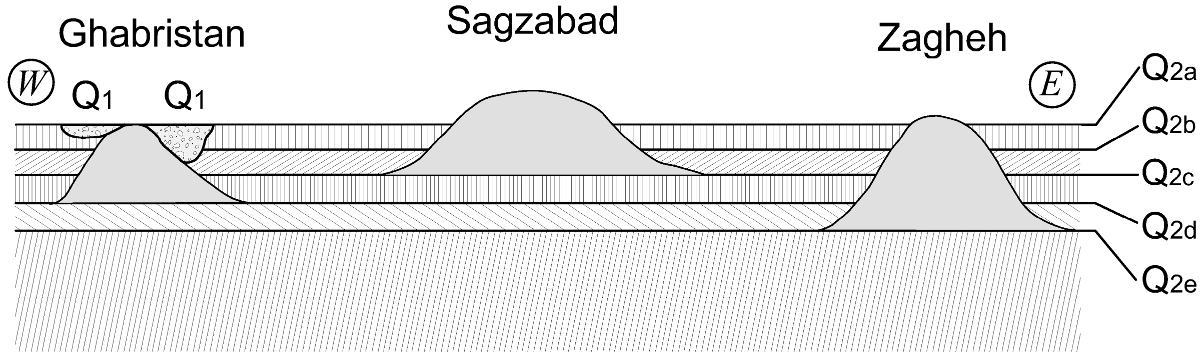

Figure 3. Schematic stratigraphy of fan aggradation around the Sagzabad Cluster, approximate section west-east. The tells of Zaghe, Ghabristan and Sagzabad were established on sequential fan surfaces Q_{2e} to Q_{2c}. In addition, Q_{2a} and Q_{2b} relate to archaeological Scenarios 1 and 2, respectively (see text).

The reason for the remarkably long settlement hiatus in the Early Bronze Age is unknown and the subject of particular interest. Although a disruption of the social fabric through the Kura-Araxes peoples had been considered (Fazeli Nashli & Abbasnezhad Sereshti 2005) it is important to also analyse the palaeoenvironment during that period to evaluate its possible impact on settlement shifts of past societies. The main concerns are the impact of local climate and hydrology on the agricultural regime, the possible influence of large earthquakes, and the relationship between alluvial fan aggradation rates and the growth of the settlement mounds due to continuous demolishing and rebuilding of mud-brick structures.

The wider Qazvin Plain has been the focus of several recent archaeological investigations allowing to establish an accurate chronology from the earliest pottery-Neolithic finds (ca. 8000 yr BP) to the Iron Age period (ca. 2500 yr BP), and highlighting the increase of cultural and bioarchaeological complexity. Plant remains showed an increase of domesticated species, particularly pronounced at the beginning of the Transitional Chalcolithic period (ca. 7200 yr BP) when pottery styles changed profoundly (Fazeli Nashli *et al.* 2009) and craft production became more specialised (Matthews & Fazeli 2004). In contrast, an analysis of animal bones from several habitation sites showed no clear trends during the prehistoric period (Young & Fazeli 2008) but highlighted an apparent increase of wild hunted animals at the Iron Age site of Sagzabad (Mashkour *et al.* 1999).

3. Holocene climate change in the study area

Only few palaeoclimate proxy data exist for the Holocene in Iran (Kehl 2009) and the best proxies for the study region come from palynological analysis of sediment cores from Lakes Zeribar, Mirabad and Urmia (Fig. 1) (van Zeist & Wright 1963; van Zeist 1967; van Zeist & Bottema 1977; van Zeist & Bottema 1982; Bottema 1986; van Zeist & Bottema 1991). Recently, the cores from Zeribar and Mirabad were re-analysed for $\delta^{18}O$ (Stevens *et al.* 2001; Stevens *et al.* 2006) and palaeolimnological indicators (Griffiths *et al.* 2001; Wasylikowa *et al.* 2006). Further studies were undertaken at Lake Urmia (Djamali *et al.* 2008b; Djamali *et al.* 2008c) and new sediment cores extracted from Lakes Almalou (Djamali *et al.* 2009) and Maharlou (Djamali *et al.* 2008a). Although analysis of these proxy data is challenging, valuable palaeoclimatic information can be derived for our study area.

Some authors were uncomfortable with the chronology of sediment cores from Lakes Zeribar and Mirabad (Jones & Roberts 2008) and Stevens *et al.* alluded to a possible, albeit unknown, hard-water effect for Lake Zeribar (2001). To investigate this further we recalibrated for both lakes the original pollen spectra (Garnier N.D.) and radiocarbon dates (Stevens *et al.* 2001; Stevens *et al.* 2006) using OxCal V4.0 (Bronk Ramsey 1995; 2001) and linear age-depth models, implemented by Dep-Age V3.9 (Maher 1998). The model for Lake Mirabad is robust as only charcoal samples were used for the ^{14}C dating (Stevens *et al.* 2006: their Fig. 2). Based on the calibrated dates it seems unlikely that the samples from Lake Zeribar are hard-water aged since an overall fit of the data would result in a termination date of the core that is considerably too young, not too old. Given the overall robustness of Lake Zeribar's chronology (Roberts *et al.* 2008) and its good correlation with Lake Mirabad for pistachio and oak pollen (see below) we therefore consider the data to be reliable. However, our calibrated results differ from previously published diagrams (Stevens *et al.* 2006: their Fig. 4a), which can be attributed to discrepancies in the depth assignment of sample GrN-7628[3].

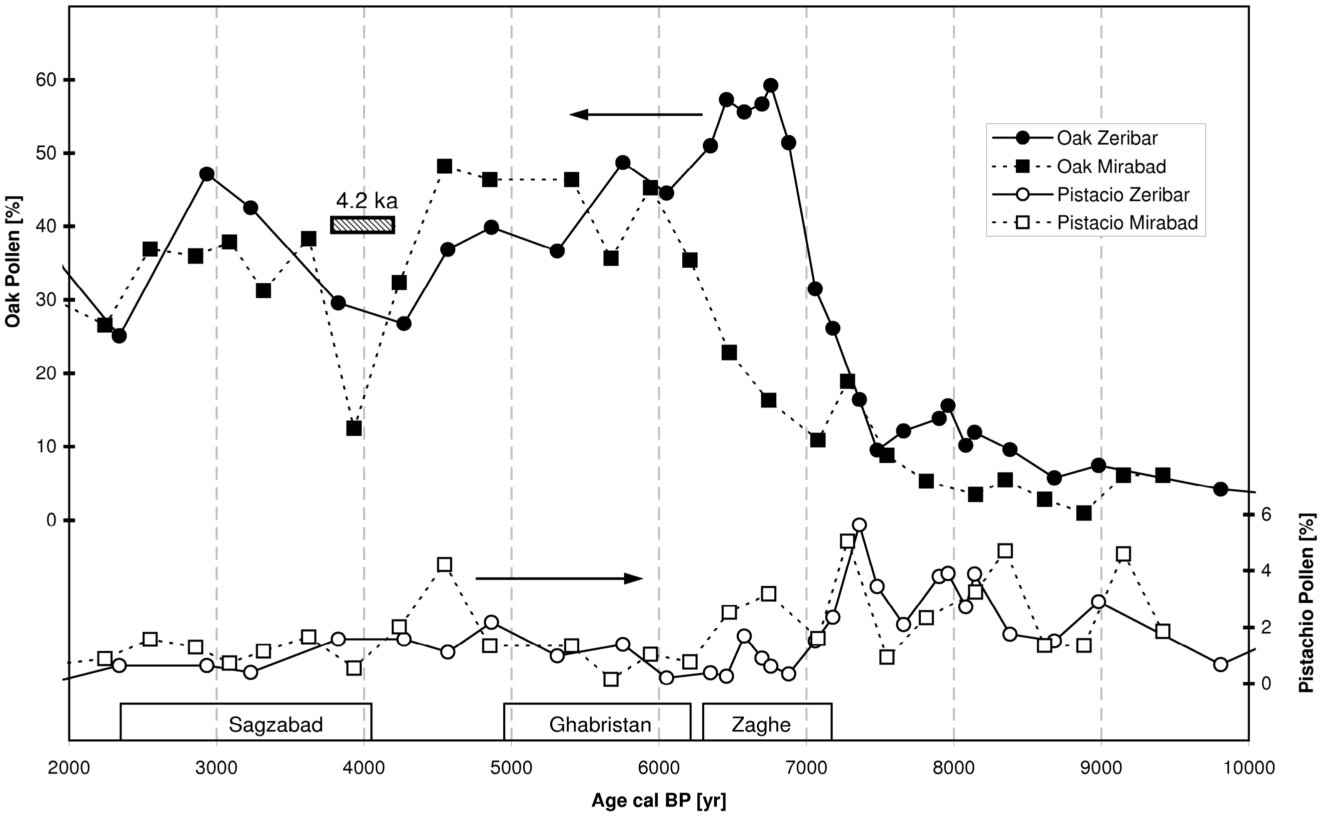

Figure 4. Calibrated pollen sequence (oak - top and pistachio – bottom; different scales) for Lakes Zeribar and Mirabad during the Holocene. For the age-depth conversion constant sedimentation rates were used between calibrated radiocarbon dates (see text). The bottom part of the diagram shows the settlement sequence for the Sagzabad Cluster. The '4.2 ka BP event' is indicated by a horizontal bar (Staubwasser & Weiss 2006).

The palynological data indicate an *Artemisia* and chenopod steppe during the Last Glacial Maximum (Stevens *et al.* 2001; Stevens *et al.* 2006) that changed in the early Holocene, ca 9500 yr BP, into a grass dominated savannah, with few oak trees and varying pistachio abundance. It was

[3] We estimate that Stevens *et al.* (2006) placed sample GrN-7628 at 1085 cm, not 985 cm.

followed by a marked decrease of pistachios around 7200 yr BP (Fig. 4). Pistachio pollen spectra for Lakes Zeribar and Mirabad are virtually synchronous, confirming the reliability of the age-depth model for Lake Zeribar. Changes in oak pollen are also mostly synchronous between the two sites, apart from the period between 7300 and 5300 yr BP, when the data from Lake Mirabad show a distinct lag of ca. 800 years. During the period of fluctuating pistachio concentration, oak pollen gradually rose followed by a steep increase from 7500 yr BP. At Lake Zeribar oak forests reached their greatest distribution at 6750 yr BP and then steadily declined from 6450 yr BP onwards to enter a pronounced depression in 4550 yr BP that recovered in 3250 yr BP. It dropped again after 2950 until 1850 yr BP, when stable levels were reached that were maintained until ca. 700 yr BP. At Lake Mirabad the oak pollen rose later and more slowly. It only reached the levels of Lake Zeribar in 6000 yr BP. The depression in oak pollen observed at Lake Zeribar is also seen, and somewhat sharper, at Lake Mirabad, lasting from 4550 to 3600 yr BP, about the same time as the often quoted '4.2 ka BP event' (i.e. 4200 to 3800 yr BP) (Staubwasser *et al.* 2003; Mayewski *et al.* 2004; Arz *et al.* 2006; Staubwasser & Weiss 2006; Kaniewski *et al.* 2008).

The main limiting factor for oak is total moisture availability during the length of its growing seasons, including spring rains. Pistachio is more drought resistant but limited by cold winters. In conditions that allow the growth of oak forests, pistachio is usually suppressed (Stevens *et al.* 2001). The dominance of pistachio until 7200 yr BP is hence taken to indicate a dry early Holocene climate with moderate temperatures. The increase of oak pollen in the mid-Holocene is attributed to higher moisture availability. This climate scenario differs somewhat form records for other areas of the Middle East that show high moisture input during the early Holocene (Bar-Matthews *et al.* 1997; Bar-Matthews *et al.* 1999; Kaniewski *et al.* 2008) but it is corroborated by palaeolimnological investigations at the two lakes considered here (Griffiths *et al.* 2001; Wasylikowa *et al.* 2006). Possible reasons for this discrepancy have been discussed by various authors (Stevens *et al.* 2001; Stevens *et al.* 2006; Roberts *et al.* 2008). Stevens *et al.* complemented the palynological data with isotope studies (2001; 2006) and argued that the $\delta^{18}O$ variation are mainly an indicator of the seasonality of precipitation whereby longer winter/spring precipitation season ("continental climate") provided the additional moisture input that supported the growth of oak forests. Jones & Roberts (2008) highlighted other factors that may possibly have influence the oxygen isotope record (e.g. total annual precipitation, temperature, depletion of heavy isotopes along storm tracks, source of water). To analyse this further we interpolated modern precipitation data (Willmott & Matsuura 2001). Very similar modern precipitation seasonality was found for the two lakes but the total amount of annual rainfall differs greatly, with 901 mm for Lake Zeribar and 380 mm for Lake Mirabad, most likely linked to their different elevations of 1268 m and 800 m a.s.l., respectively. It is therefore conceivable that their similar modern vegetation patterns indeed result from an equivalent seasonality of precipitation. This allows associating the pollen spectra with variations in total precipitation and duration of the rainy season.

In the Zagros Mountains seasonality of climate is determined by the interactions of rain-bearing westerlies from the Mediterranean, the Siberian high in winter that blocks their progress, and hot winds emanating from Iran's Central Plateau in summer that deflect the westerlies along the western foothills of the mountain range (Evans *et al.* 2004; Stevens *et al.* 2006). Lake Zeribar lies along a track of the westerlies over the Zagros Mountains towards the north, where they are only affected by minor tracks of the hot summer winds from the Central Plateau. In contrast, Lake Mirabad is located on the southwestern flanks of the mountain range, where the summer winds that originate in the centre reach strongly over the mountains to deflect the westerlies towards the southeast (Evans *et al.* 2004). A small weakening of the summer winds could therefore have greatly suppressed their influence at Lake Zeribar, while such small change may have had only little influence at Lake Mirabad. This model of sensitivity to absolute levels of change can hence explain the lag between climate improvements at Lake Mirabad, compared to Lake Zeribar, as an expression of weakened summer winds during the mid-Holocene. It also allows using the oak pollen record of Lake Zeribar as a sensitive analogue for the onset of hot summer winds over the Central Iranian Plateau and thereby as a proxy for the overall moisture input into the study area, given that no other measurements are available. When compared with the archaeological chronology, the onset of the Transitional Chalcolithic style and the settlement of Zagheh (from ca. 7170 yr BP) generally coincides with an increase in oak pollen (i.e. moisture) after ca. 7500 BP; the occupation of Ghabristan (6215-4950 yr BP) is in a time of steadily declining moisture; and the settlement hiatus includes the strongest aridity at ca. 4300 yr BP. The resettlement and occupation at Sagzabad (4050-2350 yr BP) spans an interval of initially increasing moisture that decreased again after 2950 BP reaching a minimum at 2350 yr BP, coincident with the end of settlement at this site. The increase of wild hunted animals in people's diet coincides with this more arid climate.

4. Holocene earthquakes in the study area

Iran is part of a tectonically active, diffuse boundary zone between the Arabian and Eurasian tectonic plates (Fig. 1), which converge at rates of ~20-25 mm yr^{-1}(Sella *et al.* 2002; Vernant *et al.* 2004). The Central Iranian Plateau hosts several active faults with slip rates > 1 mm yr^{-1} (Bachmanov *et al.* 2004; Fattahi *et al.* 2006; Fattahi *et al.* 2007; Le Dortz *et al.* 2009; Walker *et al.* 2010) and has experienced several destructive earthquakes in the last century, including the 1953 M_W 6.5 Torud, 1962 M_W 7.0 Buyin Zara and 2002 M_W 6.4 Changureh earthquakes (Ambraseys & Melville 1982; Walker *et al.* 2005). The epicentre of the Buyin Zara event was located ~22 km SSE of the Sagzabad tells. This event killed over 12,220 people and damaged beyond repair ~21,330 homes in 300 villages throughout the region (Ambraseys 1963). The earthquake generated a discontinuous series of surface ruptures along the Ipak Fault with a total length of ~95 km. Modified Mercalli Scale seismic intensity was estimated at VIII and IX in the ~15 km wide region bounding the Ipak fault, and VII in the region encompassing the Sagzabad Cluster (Fig. 2) (Ambraseys 1963; Berberian & Yeats 2001). Based largely on archaeological investigations by Negahban (1971; 1973; 1974a; b; 1976; 1977), Berberian & Yeats (2001) speculated that the Sagzabad settlement was destroyed by an earthquake of similar or greater magnitude to the 1962 Buyin Zara event at ca. 4010-3510 yr BP. Bachmanov *et al.* (2004) reported vertical offsets of presumed lower and middle Pleistocene deposits of 2–3 m along the western Ipak fault, left-lateral separations of 85-90 m from the "oldest generation of fans" near the settlement of Ipak, and offsets of 25 and 30 m of Late Pleistocene terraces across the eastern Ipak Fault (see also Ambraseys 1963). The location of these sites was not reported and hence these interpretations could not be verified. Since no dating of the fault-related sediments was conducted, the timing of earthquakes at these locations is unknown.

Recent palaeoseismic studies of this region by our group (Quigley *et al.* 2011) revealed the presence of a NW-trending, >20 km long, ~0.75 to 1 km wide, elongate zone of anomalous, mildly elevated and steeply dissected topography that runs from south of the Danesfahan quarry, through the village of Cheskin, to the village of Rudak (Fig. 2). On the basis of the morphology of this structure, the lateral continuity with the Ipak fault, the absence of any defined surface ruptures, and the changes in stream morphology across the structure, Quigley *et al.* (2011) interpreted this feature as an anticlinal fold that developed above a 'blind' thrust fault at depth, and termed this the Cheskin Anticline. The underlying fault appears to consist of at least two NE-dipping strands as indicated by the overall cross-sectional topographic asymmetry of the uplift and the sharp increases in slope on the SW-facing flanks of the SW edge and central part of the anticline (Figs 2 & 5b).

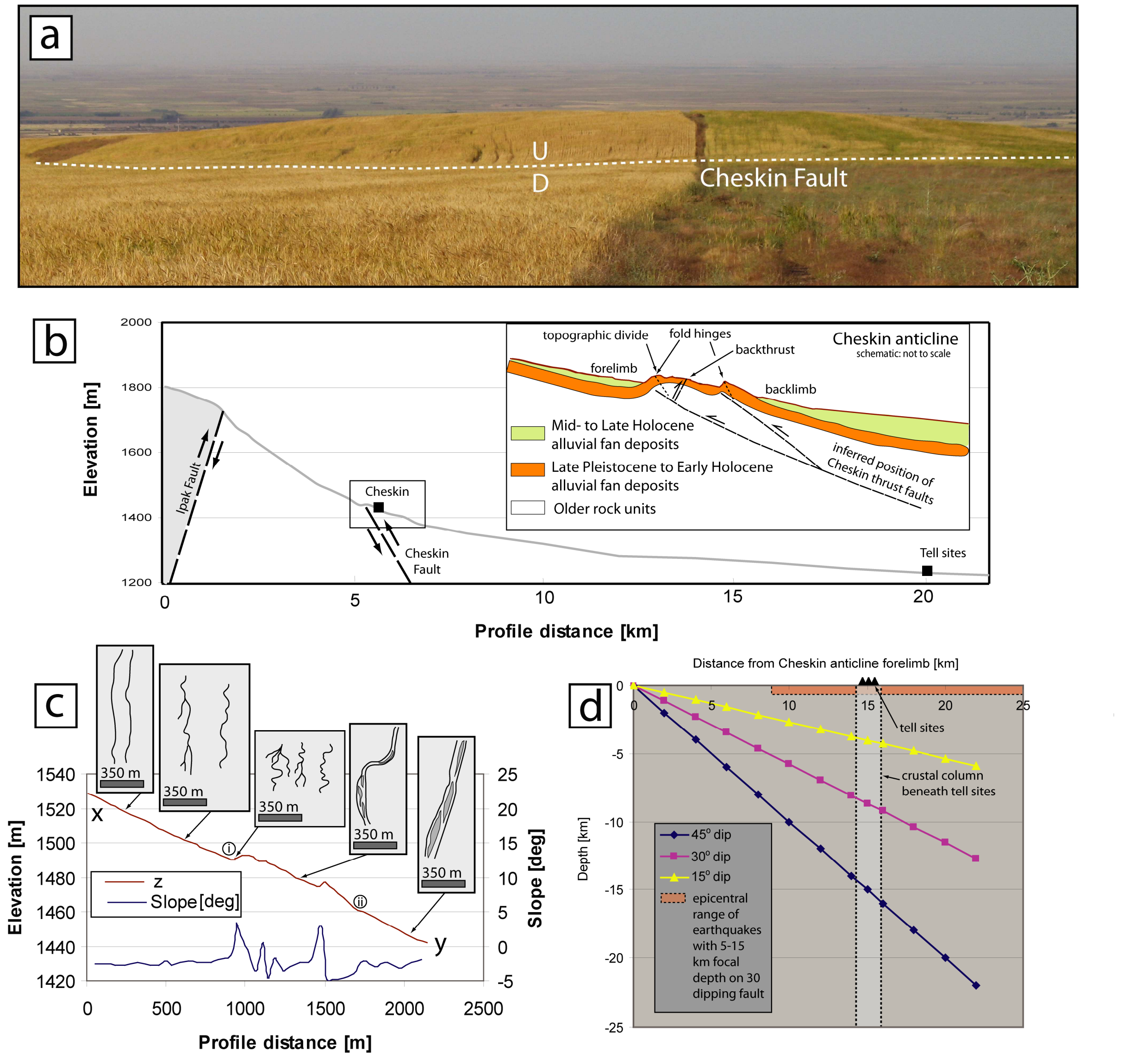

Figure 5. Tectonic geomorphology of the Cheskin Anticline and underlying thrust fault. All sections oriented at an azimuth of ~030^o with a look direction to the WNW. (a) View looking north from alluvial surface across the Cheskin Anticline, showing prominent topographic expression associated with hangingwall folding and uplift. Inferred position of Cheskin Fault shown. (b) SSW-NNE oriented topographic cross-section from Ipak Fault to the Sagzabad Cluster tell sites, showing inferred dip of the Ipak and Cheskin Faults. Location of inset as shown. (Inset) Schematic topographic and geological cross-section of the Cheskin Anticline, showing inferred position of the Cheskin thrust faults and backthrust, major features of the fold (forelimb, hinge, backlimb) and distribution of alluvial fan deposits; see text for interpretation. (c) Total Station derived topographic profile and slope distributions across the Cheskin Anticline, showing reversal of slope from NE dipping (negative slope) to SW dipping (positive slope) across the anticline. Slope changes and airphoto interpretation reveal topographic steps associated with the faults shown in (b). Slope data also shows the lack of a subsided region in the forelimb (i) and a slightly subsided region in the backlimb (ii) relative to mean fan slope. Changes in channel geometry shown for representative channels traced directly from remotely sensed imagery. Changes in sinuosity, channel width and character reflect changing slope and bedload flux related to folding. (d) Estimated subsurface position of the Cheskin Fault for a range of possible fault dips plotted against distance from the anticlinal forelimb. Preferred fault dip of 30^o based on anticline geometry results in fault depth of ~8 km beneath Sagzabad tell sites, well within the 5-15 km depth range for typical hypocentre depths associated with Iranian earthquakes.

By comparing the anticline's geometry with predicted fold geometries from elastic half-space models (Ellis & Densmore 2006), Quigley *et al.* (2011) concluded that the morphology of the Cheskin Anticline is best explained by an underlying fault dip of ~30±10^{o} to the NNE (Fig. 5). 'Blind thrust' fault earthquakes are common in Iran (Berberian & Yeats 2001; Bachmanov *et al.* 2004; Walker *et al.* 2005) and given the lack of surface ruptures, are typically recognized by surface folding, springs and drainage diversions (Lettis *et al.* 1997; Walker *et al.* 2005; Jackson 2006), all of which can be observed adjacent to the Cheskin Anticline (Fig. 2) (Quigley *et al.* 2011). Northward projection of the Cheskin Fault (Fig. 5d) places the fault at seismogenic depths (5-15 km) beneath the Sagzabad tells, indicating that location of earthquake hypocenters associated with this fault are likely to have been in close proximity to the tell sites. Large earthquakes on this fault would have resulted in peak horizontal ground accelerations at the tell sites of >0.3g, and coupled Cheskin-Ipak Fault ruptures would have resulted in values of >0.4g, well in excess of likely limits to cause the collapse of adobe structures (~0.2g). Based on our OSL dating of samples from the Cheskin Anticline and palaeoseismic evidence we conclude that the Cheskin and Ipak Faults ruptured synchronously during large (M_W ~7.1) earthquakes from ca. 8830 to 2150 yr BP with a return period of ~500-1,000 years, thus overlapping in time with the occupation of the tell sites (Quigley *et al.* 2011). Poisson modelling assuming a periodic model for earthquake recurrence indicates a 66% probability of one earthquake of M_W ~7.1 occurring during occupation of Zagheh, a 79% probability for Ghabristan, and an 88% probability for Sagzabad; the probabilities for two earthquakes are derived from this model as 42%, 55% and 65%, respectively (Quigley *et al.* 2011). These calculations make it very likely that the settlements were affected by at least one earthquake, although no such damage is evident in excavations at Zagheh and Ghabristan. However, some destruction layers in the Sagzabad tell were already ascribed to palaeoseismicity (Berberian & Yeats 2001).

5. Holocene alluviation in the study area

In order to investigate the spatial and temporal relationships amongst alluviation and human settlement on the Hajiarab fan, we conducted mapping and targeted OSL dating of 14 sedimentary deposits adjacent and in close proximity to the tell sites and on other parts of the alluvial landscape (Table I). The OSL sampling and processing procedures were analogous to those described by Fattahi *et al.* (2006). On this basis we divided Pleistocene to Holocene alluvial deposits into three packages. The oldest recognized alluvial fan deposits (Q_3) are no longer served by the fan. They consist of coarsely bedded, moderately sorted, strongly imbricated coarse-grained conglomerate and sandstone units deposited as unconfined sheetflows under high energy conditions. The later deposits (Q_2) were laid down through sheetflows and consist of interbedded silt, gravel and loam units that were subsequently incised by an intricate channel network (Q_1, Fig 2). The occurrence of these packages throughout the fan is not necessarily contemporaneous and especially the transition zone from sheetflow to channelized deposits (Q_2 to Q_1) prograded to the more distal parts of the fan over time. However, in small areas like the Sagzabad Cluster, structural and chronological developments coincide.

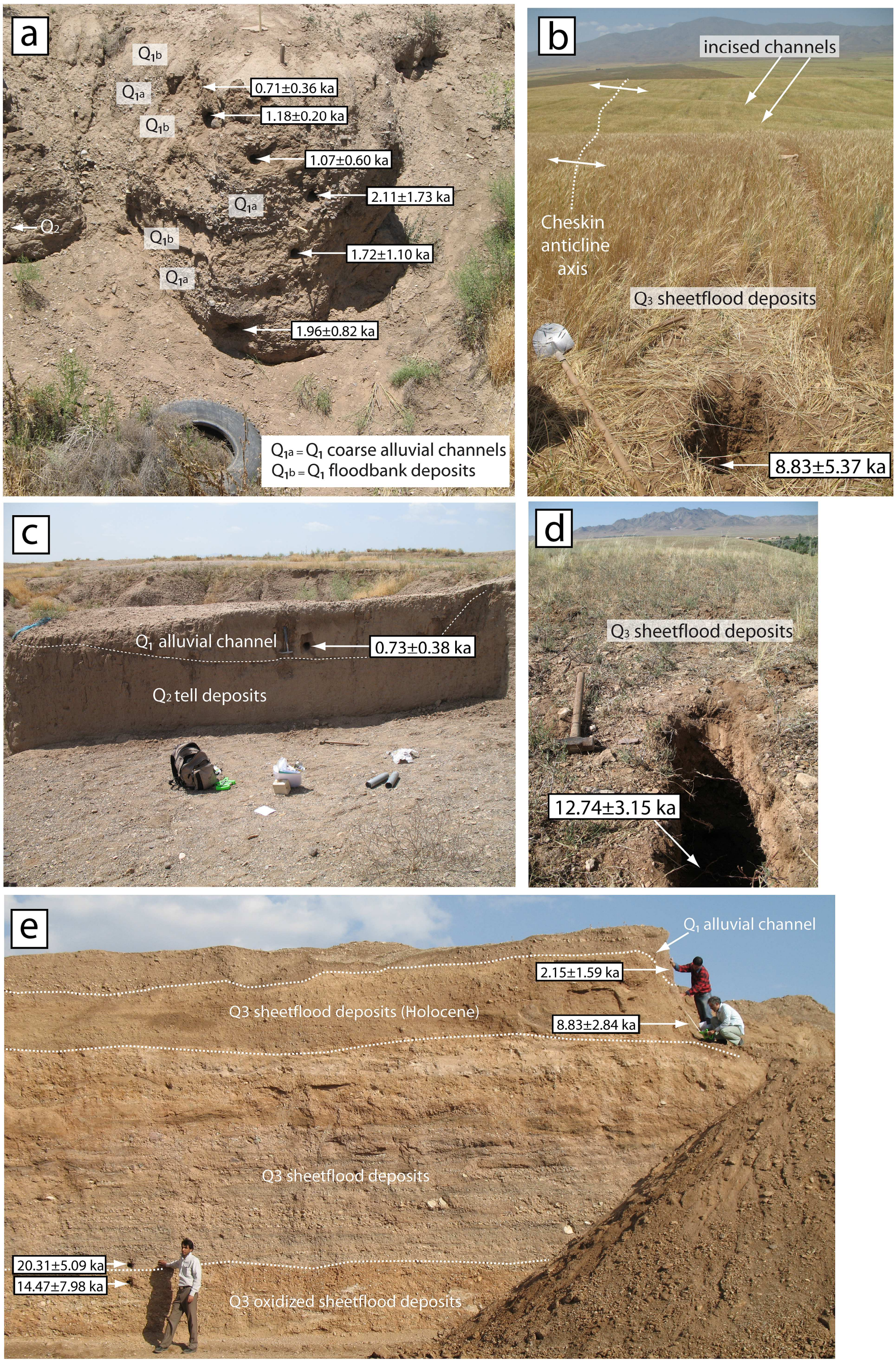

Figure 6. (a) OSL samples GA01-06 and corresponding ages from Q_1 alluvial channel southwest of Ghabristan. Channel is interpreted to have incised into tell deposits (out of picture). Stratigraphic packages divided into coarse-grained alluvial channels (Q1a) and sandy silts (Q1b) that are interpreted as floodbank deposits. Repeated oscillation between these deposits implies deposition in a braided stream environment with frequent thalweg shifts. (b) CF02 sampling pit site and OSL age from crest of Cheskin Anticline. (c) GB01 sampling site and OSL age from Q_1 sand channel incised into Ghabristan Q_2 deposits. (d) CF01 sampling pit site and OSL age from warped alluvial fan east of Cheskin. (e) MINE01-04 sampling sites and OSL ages from Danesfahan quarry, and stratigraphic boundaries.

Table I: OSL data for 14 sediment samples. Dose rates were derived from soil moisture and chemical composition of sediments around the sampling tube and the OSL ages determined form the measured equivalent dose and the dose rate. The error in the OSL age is derived from the errors in these two measurements and is given as one standard deviation. For technical details of the OSL sample preparation and measurements see Fattahi et al. (2006).

Sample	***Description***	***Depth [m]***	***Age [yr BP]***	***ΔAge [yr BP]***
Channel fill east of Ghabristan:				
GA1	Conglomerate I	2.48	1960	820
GA2	Silty sand	1.84	1885	1375
GA3	Conglomerate II	1.37	2110	1730
GA4	Sand	1.07	1070	600
GA5	Conglomerate III	0.75	1180	200
GA6	Silty sand	0.45	710	360
Shallow channel west of Ghabristan:				
GB1	Sand	0.52	730	380
Bottom of excavation pit north of Ghabristan:				
GC1	Gravel	2.10	1680	340
Quarry west of Danesfahan:				
MINE01	Cemented debris-flow conglomerate	6.05	14470	7980
MINE02	Sheet-flow conglomerate and gravel	5.60	20310	5090
MINE03	Sheet-flow gravel and conglomerate	1.78	8830	2840
MINE04	Channel-flow sand and gravel	0.80	2150	1590
Alluvial fan east of Cheskin:				
CF01	Conglomerate	0.60	12740	3150
Alluvial fan above Cheskin Anticline:				
CF02	Conglomerate	0.62	8840	5370

In the quarry west of Danesfahan (Fig. 6e), the sheetflood deposits (Q_3) are well cemented and more oxidised at the bottom, and weakly cemented, loosely consolidated and upward-fining to a medium-grained sand towards the top. They are cut by Q_1 channels and filled with late Holocene alluvia. Similar Q_1 channels also incise into the Cheskin Anticline creating the interrupted segments visible on the satellite images (Fig. 2). The two deepest OSL samples obtained from the quarry show age inversion (MINE01 and MINE02, see table I). Although this may be caused by a disconformity visible between them, the two ages are indistinguishable within their respective error ranges, as the samples proved particularly difficult to date. MINE03 is the last sample from sheetflood style unconfined deposits before Q_1 channel deposits were encountered in MINE04, thereby providing an age bracket of 8830 - 2150 yr BP for the date of this transition. Overall the OSL ages indicate that the sequence exposed in the quarry spans a period of ≥18,000 years. Given the age inversion for the oldest samples, calculations of sedimentation rates are subject to error but an estimate of 0.5 mm yr^{-1} can be made for the interval of ca. 14,470 - 8830 yr BP. By similar method, the sedimentation rate between 8830 and 2150 yr BP is evaluated as ~0.2 mm yr^{-1}, although truncation of alluviation by the Q_1 channel, and thereby a larger rate, is possible (see Fig. 6e).

The tells of the Sagzabad Cluster were established on gradually aggrading Q_2 surfaces (Q_{2e} - Q_{2c}; Fig. 3) and in this area the mostly fine-grained fan deposits were mixed with cultural material. The fully established sheet aggradation (Q_{2a}) buried most of the tells and was later cut by a channel network that filled with late Holocene deposits (Q_1).

To investigate the relationship between fan surfaces and dated archaeological occupation layers several test trenches were excavated in the surroundings of the tells. A trench that was dug through a channel (Q_1) in the orchard east of Ghabristan encountered 4.2 m of channel fill before reaching the Q_2 material, initially interspersed with archaeological pottery down to 4.7 m (i.e. Q_{2d} ~ 4.7 m). A 9.8 m deep sondage trench was opened south of Sagzabad, where nearly all alluvial deposits were fine grained (Q_2) and were interspersed with cultural material down to a depth of 3.0 m (i.e. Q_{2c} ~ 3.0 m). These results are compatible with estimates for the depth of alluvial surfaces determined from the depth of archaeological deposits (see Section 2 and Table II).

Table II: Estimated depth of alluvial facies, derived from archaeological results.

Site	Date	Alluvial facies	Minimum depth of alluvium	Comment
Zagheh	7170 yr BP	Q_{2e}	4.6 m or 6.1 m	Reported depth of 'virgin soil' reached in excavation 2001 and in the 1970s, respectively
Ghabristan	6215 yr BP	Q_{2d}	5.6 m	Reported depth of 'virgin soil' reached in excavation 2001
Sagzabad	ca. 4050 yr BP	Q_{2c}	2.7 m	Lowest excavation level visible.
Ghabristan cemetery, Scenario 1	ca. 3000 yr BP	Q_{2a}	0 m	Iron Age graves in a braided channel landscape
Ghabristan cemetery, Scenario 2	ca. 2500 yr BP	Q_{2b}	ca. >1m	Iron Age graves elevated on Ghabristan 'mound'

Given that Ghabristan was used as an Iron Age cemetery at around 2500 yr BP, two relevant geomorphological scenarios are feasible. In the first the fan aggradation had been completed (Q_{2a}) and channels were well established, demarcating the alluvial landscape, when the site was used for burials. The channel east of Ghabristan that separates Ghabristan and Sagzabad may already have been entrenched. This would mean that by approximately 3000 yr BP the fine grained alluvial deposits had reached their maximum thickness (Q_{2a}) to be then cut by channels (Q_1). In the second scenario the graveyard was established during the sheetflow regime and must have stood proud of the still growing alluvial plain (Q_{2b}), at least by ca. 1 m so that the graves were not constantly flooded but offered a prominent ritual focus. The alluvial sediments would hence still have been below their maximum level (Q_{2a}) at that time. Both arguments have considerable cultural merit but also raise practical and functional issues of land use. The results of these geomorphological considerations are summarised in Table II.

The reported depth of the archaeological stratigraphy from the 2001 excavation at Zagheh is surprisingly shallow. As this site is located about 2 km further into the distal part of the fan, the alluvial aggradation there could have been somewhat less. Alternatively, the excavation trench may have been located on what was, at the time when the tell was started, slightly raised land and the depth reported from the 1970s trench may hence represent the overall alluvial depth better. It is here used for further calculations.

Using these results it is possible to estimate alluviation rates to be 0.5 mm yr^{-1} between 7170 and 6125 yr BP, and 1.3 mm yr^{-1} between 6125 and 4050 yr BP (i.e. including the period of settlement hiatus). Thereafter Scenario 1 leads to a relatively high aggradation rate of ca. 2.6 mm yr^{-1} until ca. 3000 yr BP, while Scenario 2 involves a rate of less than 1.1 mm yr^{-1} until ca 2500 yr BP.

Since the late Holocene braided channels (Q_1) cannot be chronologically constrained by habitation events, samples for OSL dating were extracted. The settlement mound of Ghabristan is incised in the west by a 5.9 m wide, ~0.7 m deep, well sorted and bedded sand channel, indicating that channel formation occurred after settlement abandonment (Fig. 6c), which is confirmed by the OSL age of 730 yr BP. Another channel, exposed in an archaeological excavation trench borders the tell to the east. Its fill (Fig. 6a, OS1, Q_1) consists of interbedded coarse pebbly conglomerate and silty sands to a depth of ≥3.1 m. The conglomerates contain moderate imbrication and suggest deposition in a series of meandering braided streams with rapidly changing channel networks and palaeoflow to the NNE. The sands contain thin (≤1mm) laminations and are interpreted as floodbank deposits. This alluvial sequence laps on to the edge of the Ghabristan tell, and it was initially speculated that channel alluviation may have inundated the tell during human occupation. However, six OSL samples from this channel (GA1-6) reveal that the age of the channel fill (~710-2110 yr BP) post-dates Ghabristan's abandonment by at least 2840 years. The shallowest sample correlates well with the results obtained from the western channel in terms of depositional facies and age, suggesting that these units were deposited synchronously as part of a broad stream channel network (Q_1) at around 700 yr BP. The sample obtained from the bottom of the excavation pit north of Ghabristan (GC1) yields an age of 1680 yr BP. The elevation of the sample location, the conglomeritic facies, and the age is consistent with the basal part of channel deposits from the eastern channel, linking the northern position into the channel network (Q_1). Given that the eastern channel cuts through all visible Q_2 deposits, the aggradation must have been complete (Q_{2a}) before 2110 yr BP, resulting in an average alluviation rate between 4050 and 2110 BP (Q_{2c} to Q_{2a}) of 1.5 mm yr^{-1}. When fitted linearly, the OSL dates from within the eastern channel (GA1-6) show a late Holocene channel sedimentation rate of also ~1.5 mm yr^{-1}.

The OSL ages are not of sufficient resolution to determine whether accumulation of coarse and fine grained sequences occurred as large magnitude flood 'packages', or whether they reflect separate depositional events with fluctuations in channel geometry and/or depositional energy. The presence of three coarse alluvial layers within the eastern channel implies a large flood recurrence interval of ~433 years, although this is subject to uncertainty given the error range of the OSL ages.

Using OSL dating and archaeological stratigraphic constraints, sedimentation rates were derived for the study area. However, uncertainties in some of these are large, given the errors in OSL dates, presence of disconformities between sample sites and inherent non-linearity in sedimentation (i.e. deposition during intermittent large floods). Nonetheless, these estimates provide semi-quantitative constraints on fan alluviation rates from ca. 14,470 yr BP (and possibly as late as 20,310 yr BP) to ca. 710 yr BP.

The transition from sheetflood style deposition to channelized deposition on the Qazvin Plain as recorded in the Danesfahan quarry took place between ca. 8830 and 2150 yr BP. For the distal part of the Hajiarab fan valuable information can be derived from the archaeological sequence at the tell sites, placing the transition to channel flow after ca. 3000 or 2500 yr BP (Scenarios 1 and 2, respectively), when the Iron Age cemetery in Ghabristan was in use, but before ca. 2110 yr BP, the earliest date recorded for the Q_1 channel deposits. These deposits are contemporary with the Q_1 fill from the Danesfahan quarry, implying the transition to channel deposition by ca. 2100 yr BP occurred across the study area. There is no evidence for a return to sheetflow after the establishment of the alluvial channels. If any such regime had been established after the youngest recorded channel deposits (ca. 710 yr BP) it would appear to have been truncated by erosion.

6. Discussion

By integrating geologic, geomorphic, palaeoclimatic, and chronologic datasets with the archaeological chronology of the Sagzabad Cluster, we can investigate possible links between changing environmental conditions and cultural evolution on the Qazvin alluvial plain. Increasing moisture associated with changes in Holocene climate after ca. 7200 BP may have initially provided opportunity for settlement on the Hajiarab fan by increasing water availability. It is possible that the settlement of Zagheh (ca. 7170 yr BP) was established due to the favourable climatic conditions around this time, leading to the flourishing of the new Transitional Chalcolithic pottery style. The settlement in Ghabristan (6215-4950 yr BP) was contemporaneous with a steady but slow reduction in moisture (6450-4550 yr BP), but its abandonment is not marked by a particular climatic event. If such decreased moisture reduced waterflow into the Hajiarab fan, then settlements may have been more vulnerable to droughts and the local population may have abandoned Ghabristan once a threshold was reached. It is highly likely that other cultural factors will have greatly influenced such decision. The settlement hiatus on the Hajiarab fan overlaps with peak aridity in the area.

Oak pollen data indicate an increase of moisture from 4300 to 2950 yr BP. This would be compatible with Scenario 1, under which sedimentation rates increased strongly after 4050 yr BP until the alluvial regime switched and became channelized around 3000 yr BP. The subsequent decrease of moisture input confined any further discharge to these channels, allowing inhabitants to establish the graveyard at Ghabristan in a relatively stable alluvial environment around 2500 yr BP. This view is in agreement with a suggested Iron Age date for the irrigation channel that was detected around Ghabristan through geophysical surveys (Schmidt & Fazeli 2007). This onset of wetter conditions in 4300 yr BP, after a period of aridity or reduced moisture input, may in fact be one of the reasons why the Sagzabad mound was settled at around 4050 yr BP. Climatic conditions during the occupation of Sagzabad (4050-2350 yr BP) were variable, spanning low and medium moisture regimes. It is possible that the abandonment of Sagzabad was also related to decreasing moisture after 2950 yr BP. However, despite the temptation to link the history of settlements at the Sagzabad Cluster to climatic variations it is impossible to conclude resolutely that climate change drove the settlement patterns. Rather, we suggest that climate change-induced variations in moisture may have been just one of the factors that influenced the cultural decisions made by people living on the Hajiarab fan.

Interpretation of geologic, topographic and OSL data acquired from the Cheskin Anticline indicates that large magnitude ($M_w \geq 6.5$) earthquakes occurred on a fault underlying the Sagzabad tells, probably during the time that the tells were occupied. However, the lack of a precise earthquake chronology prohibits a clear correlation between settlement histories and earthquakes. While large earthquakes on the Cheskin and Ipak Faults almost certainly would have damaged and/or destroyed the structures built in these settlements, we found no evidence for the catastrophic destruction of the tells such as was proposed for Sagzabad by Negahban (e.g. 1971) and Berberian and Yeats (2001). Given the offsets reported for the Ipak Fault (Bachmanov *et al.* 2004) it is likely that during the Holocene many large earthquakes occurred in the region, without causing settlement abandonment. However, regardless of the earthquake frequency or impact, humans colonized the Hajiarab fan for more than 4000 years, almost certainly during earthquakes along the Ipak and Cheskin Faults. Yet the sites remained preferable and thus inhabited during this time. Buyin Zara provides an ideal modern analogue. Despite the large earthquake of 1962, a sizeable population continues to reside there and many villages destroyed during this earthquake have been rebuilt, suggesting that the risk of earthquakes in this region did not deter human settlements. We found no archaeological evidence that settlement patterns, including abandonment, were influenced by large earthquakes.

The transition from more proximal, sheetflood-style sedimentation (20,310 - 8830 yr BP) to more distal, channelized sedimentation associated with Hajiarab fan deposition occurred sometime in the mid-Holocene. As sheetfloods usually occur when runoff is insufficient to promote channel flow, we suggest that the transition to channel flow may have been prompted by the increase in moisture after ca. 7200 BP, as supported from the Lake Zeribar climatic record. The increase in rainfall would have increased stream power, promoting proximal incision and channel flow, and distal aggradation. Increased channel flow and deposition into the Hajiarab fan would have made it a more suitable location for settlement. Ultimately, fan sedimentation would bury the settlement sites. However, given the available alluvial chronologies determined from OSL dating, it appears that the alluviation that buried the tell sites occurred long after the sites were vacated, and thus stream avulsion and sedimentation are not the direct cause for settlement abandonment in the Sagzabad Cluster. Even at the time of early settlements at Sagzabad, the alluvial level (Q_{2c}) was 3 m below the current level and Ghabristan's top therefore stood more than 3 m above the alluvial floodplain. The tell's abandonment was therefore not in response to it being covered by aggraded alluvial deposits.

7. Conclusions

Bringing together all measurements, observations and archaeological results, and combining them with stratigraphic insights, it was possible to chart the palaeoenvironment of the Qazvin plain in the Holocene, and the Hajiarab alluvial fan with its Sagzabad Cluster of archaeological tells. Using all available dating evidence sedimentation rates were derived for different areas of the fan and its surroundings, ranging from 0.2 to 2.6 mm yr^{-1}. Temporal constraints were also derived for the development of different fan facies and fills (Q_1-Q_3). Analysing the morphology and geology of the Cheskin Anticline allowed estimating seismic parameters for the study area and their possible implications for ancient habitations. It was shown with recalibrated pollen data from Lake Zeribar that the settlements at Zagheh and Sagzabad coincided with increasing moisture availability, which will have made the alluvial soil of the fan fertile and hospitable. Ghabristan experienced a slowly decreasing moisture regime but its abandonment does not coincide with a particular climatic event. Climate became drier, possibly even arid, between 4550 and 3250 yr BP (termed the 'Central Iranian Drought'). This appears to be different from the sharp '4.2 ka BP' drought event reported from 4200 to 3800 yr BP (Staubwasser *et al.* 2003). Since conspicuously close in time, the Central Iranian Drought might be a regionally distinct but globally linked expression of the '4.2 ka BP event', possibly affected by tropospheric variations (Staubwasser & Weiss 2006).

This project was initially set up to provide a palaeoenvironmental context for the investigation of significant changes in human habitation, as discovered in the archaeological record of the Qazvin Plain in northwestern Iran and the south part of the central Alborz Mountains (Fazeli *et al.* 2005; Fazeli Nashli *et al.* 2009). However, it soon became apparent that this remit could be expanded to examine the interactions of several earth and anthropogenic systems that in many other places have to be investigated separately. These range from geomorphological landscape changes induced by tectonic activity to climate events that altered vegetation patterns and drainage regimes. Each system on its own is already highly complex and to disentangle their inter-relationships is a challenging task. Through the integration of all available evidence a 'palaeoenvironmental narrative' was constructed that allows insights beyond the analysis of individual earth system processes or archaeological data alone.

Palaeoenvironmental reconstructions rely on incomplete data sets, often discontinues in time or space as a result of sampling requirements or deposition deficiencies. It is hence essential to use a multitude of different palaeoenvironmental parameters, either directly or derived from proxy data, to compile frameworks for the interpretation of landscapes, regions or eras. Archaeology has a special role in this multidisciplinary approach as it forms a link between the earth sciences and the realm of social entities, where ritual, spiritual, imperial and economic concerns are of considerable importance. Due to these differences earth sciences and archaeology are often treated as separate entities, merely offering the outcome of their respective research to the other discipline, sometimes even picking carelessly citations from each other that only serve to support perceived insights (Madella & Fuller 2006). Since environmental variations undoubtedly impacted on past human behaviour, some earth scientists attempted to explain changes of societal structures, settlement patterns, agricultural regimes and even the collapse of empires (Cullen *et al.* 2000) through variations in palaeoclimate, hydrology or geomorphology. However, as the past cannot be repeated like a scientific experiment, the mere temporal juxtaposition of events is no prove of a causal link (Coombes & Barber 2005). This inability to confirm theories and hypotheses about the past is of course an epistemological problem shared between earth sciences and archaeology. Earth scientists are hence criticised if stating that temporal coincidence of environmental change on the one hand, and of over thousand years of upheaval in human history on the other were to "demonstrate" (Kaniewski *et al.* 2008) a fundamental causative link between them. Similarly, postulated links between environmental changes, caused by past human populations, and the collapse of these societies (Diamond 2006), were reinterpreted by others as drivers for the development of cultural resilience (McAnany & Yoffee 2009). In this project we used archaeological results as further data to derive an evaluation of the palaeoenvironmental record that integrates geological and anthropogenic events giving equal weight to all contributing components. Bound by the same epistemological constraints we constructed a palaeoenvironmental narrative that highlights possible links between the investigated systems.

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